PHOSPHORUS REMOVAL MECHANISMS AT THE YELLOW RIVER SWEETWATER CREEK WATER RECLAMATION FACILITY, GWINNETT COUNTY, GEORGIA

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ABSTRACT

This research investigated the capabilities of the Yellow River Sweetwater Creek Water Reclamation Facility in Gwinnett County, GA. to remove phosphorus biologically. Phosphorus levels and removal locations were analyzed in plant operational units (sampling events), while in reactor experiments (pilot studies), waste was subjected to various conditions to promote biological phosphorus release and uptake. Analysis of plant conditions at the time of experimentation indicates that one-half of the plant phosphorus removal is accomplished biologically through incorporation of phosphorus in microbial cells during growth. It does not appear, however, that enhanced biological phosphorus removal (BPR) is possible due to wastestream characteristics and/or microbial population. It was noted that the basic anaerobic-aerobic sequence associated with enhanced BPR appears to be occurring with the secondary clarifier sludge blanket and return to compartment A of the nitrification basin.

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CHAPTER 1
INTRODUCTION

1.0 INTRODUCTION

The purpose of this Special Research Problem (SRP) Report is to study the removal mechanisms of phosphorus at the Yellow River Sweetwater Creek Water Reclamation Facility in Gwinnett County, GA. and to determine the following:

(1) If the influent wastestream characteristics encourage biological phosphorus removal (BPR) and more importantly, enhanced BPR.

(2) If the wastestream exhibits such characteristics, whether or not BPR or enhanced BPR occurs.

(3) Locations of BPR within the plant, if any.

In order to meet the objectives of the SRP, the following plan of action was developed:

Establish an understanding and summary of phosphorus removal from wastewater including biological pathways, chemical treatment and conditions affecting phosphorus removal.

Conduct an analysis of existing plant conditions by measuring phosphorus content of wastewater at various locations, determining the mass balance of phosphorus and to pinpoint any phosphorus removal locations. Additionally, observe typical changes in nutrient levels throughout the plant which may affect phosphorus removal. This task would be accomplished by conducting sampling events in which wastewater is analyzed over a designated period of time at various locations throughout the plant. Analyses included ammonia, nitrite, nitrate, phosphate, chemical oxygen

demand (COD), and total phosphorus.

Conduct batch reactor experiments, referred to as "pilot studies", to determine if the wastestream is capable of phosphorus release and luxury uptake and hence, enhanced BPR. Each pilot study will consist of batch reactors subjected to various conditions including anaerobic and/or aerobic environments. Samples may be analyzed for pH, dissolved oxygen (DO), phosphate, ammonia, nitrite, nitrate, COD and total suspended solids (TSS).

CHAPTER 2
BACKGROUND AND LITERATURE REVIEW

2.1 PHOSPHORUS IN WASTEWATER

Eutrophication or the aging of surface waters due to over-abundant supply of nutrients and the growth of algae has been a growing concern throughout the world. A significant contributor to the acceleration of this process is the discharge of phosphorus from wastewater treatment plants. Historically, total phosphorus effluent limits of 1 or 2 mg/L have broadly applied in many regions of the U.S. with limits established as low as 0.07 mg/L (Sedlak, 1991) to assist in controlling this aquatic nuisance problem. Noting that twenty percent of the total U.S. treatment capacity is expected to be capable of removing phosphorus in the year 2000, a percentage that is twice as great as in 1983 (Barth, 1985), further emphasizes the importance of understanding phosphorus removal operations.

Phosphate removal from wastewater involves incorporating phosphate into particulates (suspended solids) and subsequent removal of the suspended solids. The incorporation of the phosphate is accomplished chemically and/or biologically. Chemical removal involves forming sparingly soluble metal-phosphate complexes, while biological removal incorporates phosphorus in microorganisms. Although chemical systems to remove phosphates from the waste stream have been successfully and widely used, the cost of removal has been steadily rising mainly due to the lowering of phosphorus effluent standards and subsequent increase in the amount of chemicals added. As a result, the study and

implementation of biological phosphorus removal (BPR) systems is progressing rapidly.

The following sections will briefly discuss sources and forms of phosphorus found in wastewater followed by a summary of biological phosphorus removal mechanisms and techniques and chemical treatment methods for removal of phosphorus.

2.11 SOURCES OF PHOSPHORUS

Human wastes including feces, urine and waste food disposal account for between 30 and 50% of the phosphorus in domestic wastewater (EPA Design Manual for Phosphorus Removal, 1976). Phosphate bearing detergents usually used in the laundering of clothes contributes the remaining 50 to 70%. Water treatment plants may also contribute to the phosphorus content between 2 and 20% if phosphorus is used for corrosion and scale control. Industrial wastewater may increase or dilute the phosphorus concentration based on the waste stream composition.

Typical total phosphorus concentrations of domestic wastewaters range from 4 to 15 mg/L (Metcalf & Eddy, 1991) with an average of 10 mg/L (EPA Design Manual for Phosphorus Removal, 1976). The total phosphorus in influent wastestreams has generally been declining over the past decade (Sedlak, 1991). This decrease has been mainly due to the reduction of phosphorus content in household powdered detergents and the significant increase in consumer use of liquid detergents which do not contain phosphates. Additionally, industrial and commercial pretreatment systems or

pollution prevention practices have contributed to the reduction in the amount of phosphorus reaching wastewater treatment works. Due to potential variance of the phosphorus concentration in a given wastestream, sampling and analysis for phosphorus are necessary prior to plant design or retrofit.

2.12 FORMS OF PHOSPHORUS

Phosphorus is found in wastewater in three principal forms: phosphoric acid species (H_2PO_4, HPO_4 and PO_4^{-3}), polyphosphate (P_2O_7) and organically-bound phosphorus (org-P) with the last two components accounting for up to 70% of the influent phosphorus (Metcalf and Eddy, 1991). There are a number of orthophosphate species depending upon pH of the waste stream, but HPO_4^{-2} and $H_2PO_4^-$ are the predominant forms. Polyphosphate can be considered a polymer of phosphoric acid with the water removed. However, the actual form is not of significant concern since in most current practices, phosphorus is reported in total phosphorus.

2.13 BIOLOGICAL PHOSPHORUS REMOVAL (BPR) MECHANISMS

Important cellular structural components such as nucleic acids, phospholipids, proteins and nucleotides in both procaryotic and eucaryotic cells, contain phosphorus. The metabolism of polyphosphate (polyP) in microorganisms has been reviewed extensively and the most important cellular functions of polyP as stated by Kulaev (1985) are listed below:

1) The accumulation of energy-rich ATP phosphorylic residues

in an osmotically inert reserve material containing "activated phosphate".

2) Making cells more independent of environmental conditions through the accumulation of polyP reserves.

3) Regulation of ATP and other nucleotide levels in cells.

4) Fulfilling the function of ATP in some cases by direct participation in phosphorylation reactions.

5) Linking cation (e.g., K^+, Mg^+, Mn^{2+}) metabolism with that of polyP. The cations act as counterions in the polyP chains and are released into the intra cellular medium as the polyP is hydrolyzed.

6) Contributing to cellular homeostasis and osmotic regulation. In the action of statement 5, the cations are then expelled from the cell in order to maintain osmotic pressure.

2.131 PHOSPHORUS PATHWAY IN ACTIVATED SLUDGE

The most common feature of enhanced BPR in activated sludge schemes is the alternation between anaerobic and aerobic sequences. During the anaerobic stage, phosphorus is released by the biomass and is then reincorporated in the biomass together with a portion of the influent phosphorus during aeration.

Acinetobacter is one of the primary organisms responsible for removal of phosphorus in activated sludge systems (Fuhs and Chen, 1975). Other studies have shown that several organisms may be involved in BPR. Specifically, Brodisch (1985) suggested the use of *Acinetobacter calcoaceticus* and *Aeromonas punctata* as an

effective combination with the latter species fermenting carbohydrates to end products such as acetate, which would enhance phosphorus uptake ability of the *Acinetobacter*. Note, however, that the following pathway of phosphorus focuses on *Acinetobacter* as the model.

Fatty acids are produced from organic material in an anaerobic zone (fermentation) by acidogenic bacteria. The fatty acids then serve as an important substrate for the *Acinetobacter* which are taken up and stored in the form of poly-β-hydroxybutyrate (PHB). The energy required for this uptake and storage is supplied by the hydrolysis of polyP reserves. However, the success of this activity is dependent on the outcome of competition with a host of organisms, particularly denitrifiers which can take up fermentation end products under anaerobic conditions (Toerien *et al.*, 1990).

In the following aerobic stage, *Acinetobacter* is not dependent on external compounds as an energy source, but metabolize PHB. This energy produced in the presence of oxygen is used for growth and partially used to reconstitute polyP reserves. Therefore, phosphorus uptake is above normal levels since it is not only utilized for cell maintenance, synthesis and energy transport, but is also stored for subsequent use by the microorganisms. However, it is clear that other variables such as the presence of specific cations also play important roles in the metabolism of polyP bacteria (Torien *et al.*, 1990).

As mentioned earlier, the following clarification stage accumulates the sludge which containing the excess phosphorus. It

has been shown that *Acinetobacter* enhances BPR since it has the ability to form clusters that can be easily enmeshed in existing flocs (Osborne *et al.*, 1986) and has a greater density than normal bacterial cells (Suresh *et al.*, 1986). The sludge is then either recycled, wasted and/or treated in a side stream.

2.132 CONDITIONS AFFECTING BPR

In any activated sludge system, physical factors are extremely selective forces and affect BPR. For example, in the clarification stage in a BPR system, settled sludge is recycled with the accumulated biomass. If the polyP bacteria are not part of the settled floc they are "washed out" of the system. In systems which nitrogen removal is also necessary, BPR may be significantly impacted. For instance, an anoxic stage where nitrate is the electron acceptor, the selection of denitrifiers is favored because these organisms can utilize fermentation end products as energy sources. Effectiveness of BPR may also arise from an overabundance of scum-forming bacteria or filamentous bacteria, the latter of which may cause sludge bulking (a blanket developed within the clarifier that prevents settling.)

Like other heterotrophic bacteria, activated sludge bacteria require organic carbon and other nutrients for energy and synthesis. Domestic wastewater provides a nutritionally diverse substrate that contains the compounds necessary for the growth of many bacteria (Grady and Lim, 1980). However, in order to achieve specific goals such as BPR, these compounds may not be available in

proper quantities. For enhanced BPR, Osborne (1986) has shown that the readily degradable portion of wastewater is extremely important. PolyP bacteria such as *Acinetobacter* are obligate aerobes requiring a fairly restricted spectrum of substrates for rapid growth in the activated sludge process. As discussed earlier, such substrates include fatty acids, the end products of fermentation.

2.133 BIOCHEMICAL MODEL OF ENHANCED PHOSPHORUS REMOVAL

The phosphorus pathway described in the previous section is actually a biochemical model of enhanced phosphorus removal developed by Fuhs and Chen (1975). However, since this time other conceptual models have been presented in an attempt to explain the biochemical mechanisms controlling enhanced phosphorus removal.

One current model by Comeau *et al.* (1985) proposes that polyP is the source of energy for both the replenishment of the proton motive force (pmf) and for substrate storage under anaerobic conditions. The pH gradient of bacteria is decreased under the anaerobic conditions (figure 2.1) by the diffusion of substrates (such as acetate) into the cells. In an attempt to reestablish the pH gradient, the polyP bacteria use their polyP reserve either directly or via the production of ATP. The polyP reserve may also be used to generate acetyl CoA. Reduced NAD (produced from the tricarboxylic acid cycle) is then required to store the acetyl CoA as PHB. Accumulating phosphates within the cell are then expelled along with metal cations.

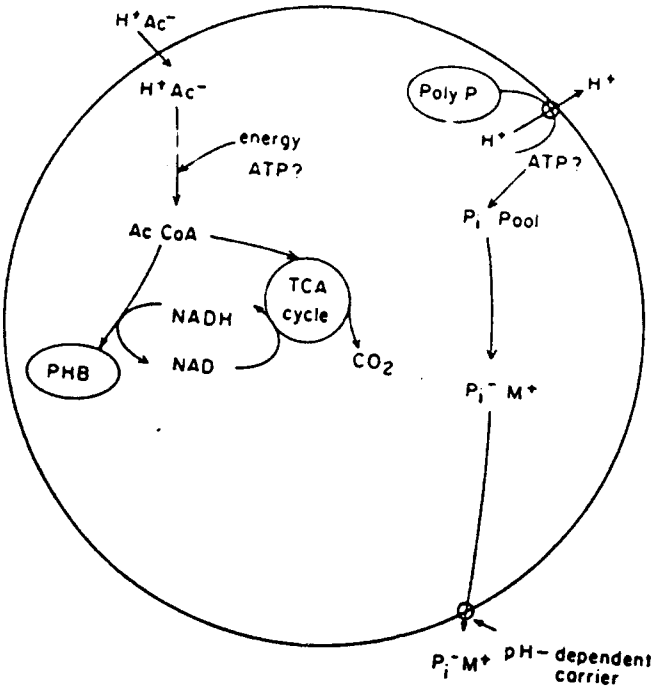


Figure 2.1 - The Comeau model for anaerobic metabolism (Comeau *et al.*, 1985). TCA, Tricarboxylic acid; Ac CoA, acetyl CoA.

Under aerobic conditions (figure 2.2), consumption of external or stored substrate will allow polyP to produce a pmf. The pmf can be used for phosphate transport and ATP production. ATP is then used for both growth and poly P storage. The metallic cations are co-transported with phosphate molecules.

If *Acinetobacter* is used as a model for polyP organisms, one can conclude the following:

1) Stored polyP is used as an energy source, fermentation end products such as fatty acids can be taken up and stored as PHB. The success of this activity varies, however, by competition with

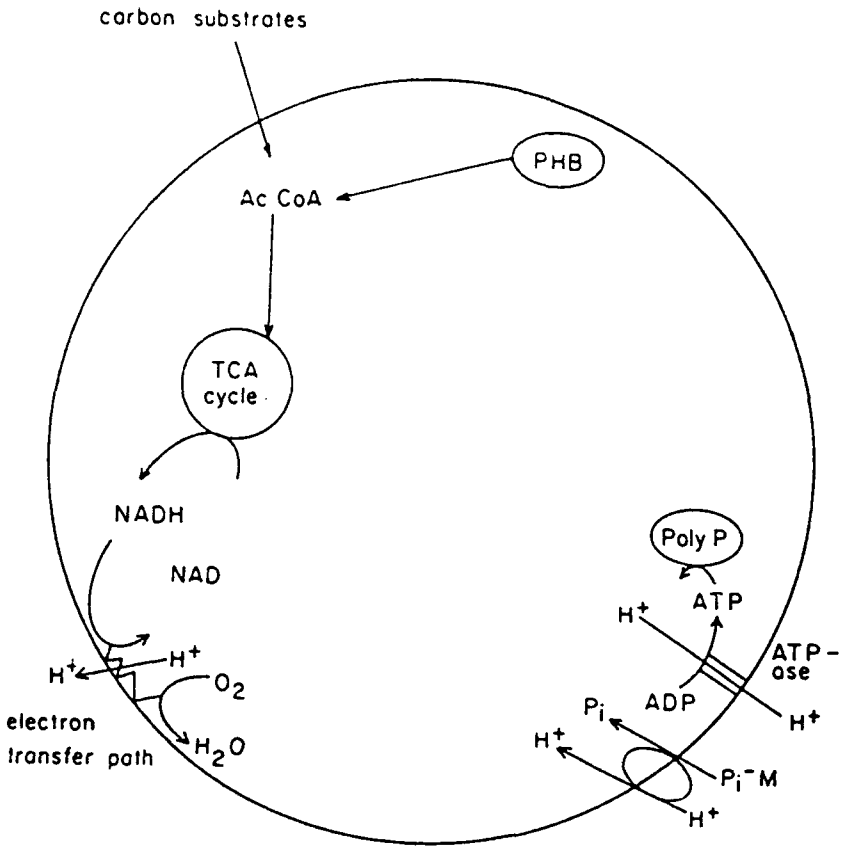


Figure 2.2 - The Comeau model for aerobic metabolism (Comeau *et al.*, 1985). TCA, Tricarboxylic acid.

other organisms such as denitrifiers which take up the end products in anaerobic conditions.

2) It uses the stored PHB as an energy source under aerobic conditions for growth and storage of polyP and is therefore, not dependent upon external compounds for energy.

Continued study of the physical and chemical factors of activated sludge systems is also critical in optimizing enhanced BPR.

2.14 BPR TREATMENT TECHNIQUES

The process of enhanced BPR in activated sludge systems is now an accepted alternative in eutrophication control strategies. Current BPR treatment techniques subject wastestreams to alternating anaerobic-aerobic conditions in which soluble phosphorus becomes part of the sludge floc accumulated in the following clarification stage. There are two categories of proprietary BPR processes, based on their nitrogen removal capabilities.

Phosphorus removal processes which are not capable of significant nitrogen removal include the Phostrip and A/O (anaerobic/oxic) systems. In the PhoStrip process, phosphorus released under anoxic conditions is used to concentrate the nutrient in a side stream for chemical treatment. The phosphorus is then precipitated, usually using lime addition. One of the simplest phosphorus removal processes is the A/O process, in which the mixed liquor passes through anaerobic and aerobic reactors followed by secondary clarification. The settled sludge is either returned to the head of the plant to become part of the mixed liquor or is wasted, resulting in phosphorus removal from the system.

Since many discharge permits require the removal of both phosphorus and nitrogen, combined processes for removal of both nutrients have been developed. Among these proprietary systems include the Five-Stage Bardenpho, A^2/O (anaerobic/anoxic/aerobic) and the Modified UCT (University of Cape Town) processes, all of

which accomplish nitrogen removal through denitrification. In the Five-Stage Bardenpho process, a sequence of anaerobic, anoxic, aerobic, anoxic and aerobic zones are followed by a clarifier. Settled sludge from the clarifier is either wasted or returned to the anaerobic zone. Mixed liquor is also recycled from the first aerobic zone to the first anoxic zone. The anaerobic zone provides the initial phosphorus release while uptake occurs in the first aerobic zone. The second aerobic zone prevents development of anaerobic conditions in the clarifier. Within proper wastewater BOD:P ratios (of which BPR is dependent), a 1.0-2.0 mg/L level of total P can be achieved (EPA Design Manual - Phosphorus Removal, 1987) with the Five-Stage Bardenpho process. The A^2/O process is similar to the A/O described earlier with the addition of an anoxic zone between the aerobic and anaerobic zones to achieve nitrogen removal. Mixed liquor is recycled from the aerobic zone to the anoxic zone at a rate 100 to 300% of the plant influent flow. The Modified UCT process separates the anaerobic and aerobic zones by two anoxic zones. The first anoxic zone receives the return activated sludge from the clarifier underflow and provides recycle to the anaerobic zone. The second anoxic zone, where a majority of the denitrification occurs receives recycled mixed liquor from the aerobic zone.

2.15 CHEMICAL TREATMENT TECHNIQUES

Chemical treatment alternatives include the addition of one of three metals: iron, aluminum or calcium. Such metals added to

wastewater react with phosphates to form insoluble complexes and are generally added upstream of the primary clarifier and/or the secondary clarifier. Formed precipitates are then removed in the subsequent clarifier or by filtration.

The most common metal salt precipitation is accomplished by the addition of ferric iron (Fe(III)), ferrous iron (Fe(II)) or aluminum (Al(III)). The most commonly used iron salts are ferric chloride ($FeCl_3$), ferric sulfate ($Fe_2(SO_4)_3$), ferrous sulfate ($FeSO_4$) and ferric chloride ($FeCl_2$). Alum ($Al_2(SO_4)_3$) and sodium aluminate ($NaAlO_2$) are the commonly employed aluminum salts. Resulting phosphorus precipitates are ferric and ferrous phosphate and aluminum phosphate. Knowledge of the metal-phosphate solubility is essential in predicting and controlling the efficiency removal. An equilibrium solubility shown in figure 2.3, diagramming iron, aluminum and also, calcium which will be described later. By maintaining the pH of the wastewater near the minimum solubility which is approximately 5.5 for $FePO_4$ and 6.5 for $AlPO_4$ metal-phosphate precipitation is maximized. Of note, is that other complexes are formed with these processes which increases solids handling requirements. Systems using iron or aluminum addition can achieve 80-95 percent total phosphorus which results in an effluent as low as 1 mg/L total phosphorus (EPA Design Manual - Phosphorus Removal, 1987). For effluent standards in the range of 0.5 to 1.0 mg/L, filtration of secondary effluent may be necessary. The advantages of iron or aluminum addition include its reliability, easy control of phosphorus removal, reduction of organic

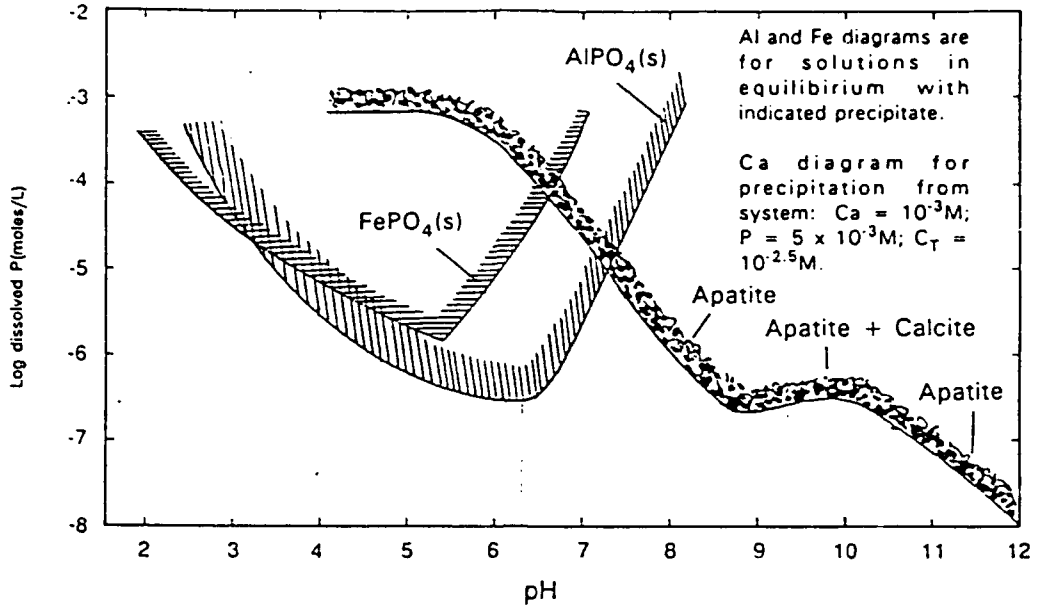


Figure 2.3 - Equilibrium solubility diagrams for Fe, Al and Ca phosphates (Ferguson *et al., 1973)*

load to the secondary clarifier and ease in retrofitting existing plants.

Phosphorus removal with lime is essentially a water softening process with the quantity of lime being dependent upon the alkalinity of the water and not the phosphorus content. Lime is added either to the primary clarifier or to the secondary clarifier effluent in a separate tertiary unit. A wide variety of calcium phosphate complexes are subsequently formed. Single-stage (low) lime treatment where the pH is maintained below 10 can achieve effluent phosphorus concentrations of 1 mg/L while effluent phosphorus concentration of less than 1 mg/L can be reached using two-stage (high) lime treatment where the pH is raised to 11-11.5.

Due to the high pH employed, concurrent biological growth is not possible; therefore lime precipitation is practiced as a pre- or post- phosphorus removal process only. Advantages of lime addition include effective heavy metal removal, simple process control and reduction of organic load to biological treatment units.

All chemical phosphorus removal processes do have significant disadvantages which have led in part to development of the biological phosphorus removal (BPR) processes. The shortcomings include high chemical costs particularly for lime addition, storage requirements for chemicals and higher amounts of sludge produced which increase dewatering and disposal costs.

2.2 YELLOW RIVER/SWEETWATER CREEK WATER RECLAMATION FACILITY OPERATIONS

2.21 PLANT STATISTICS AND OPERATION

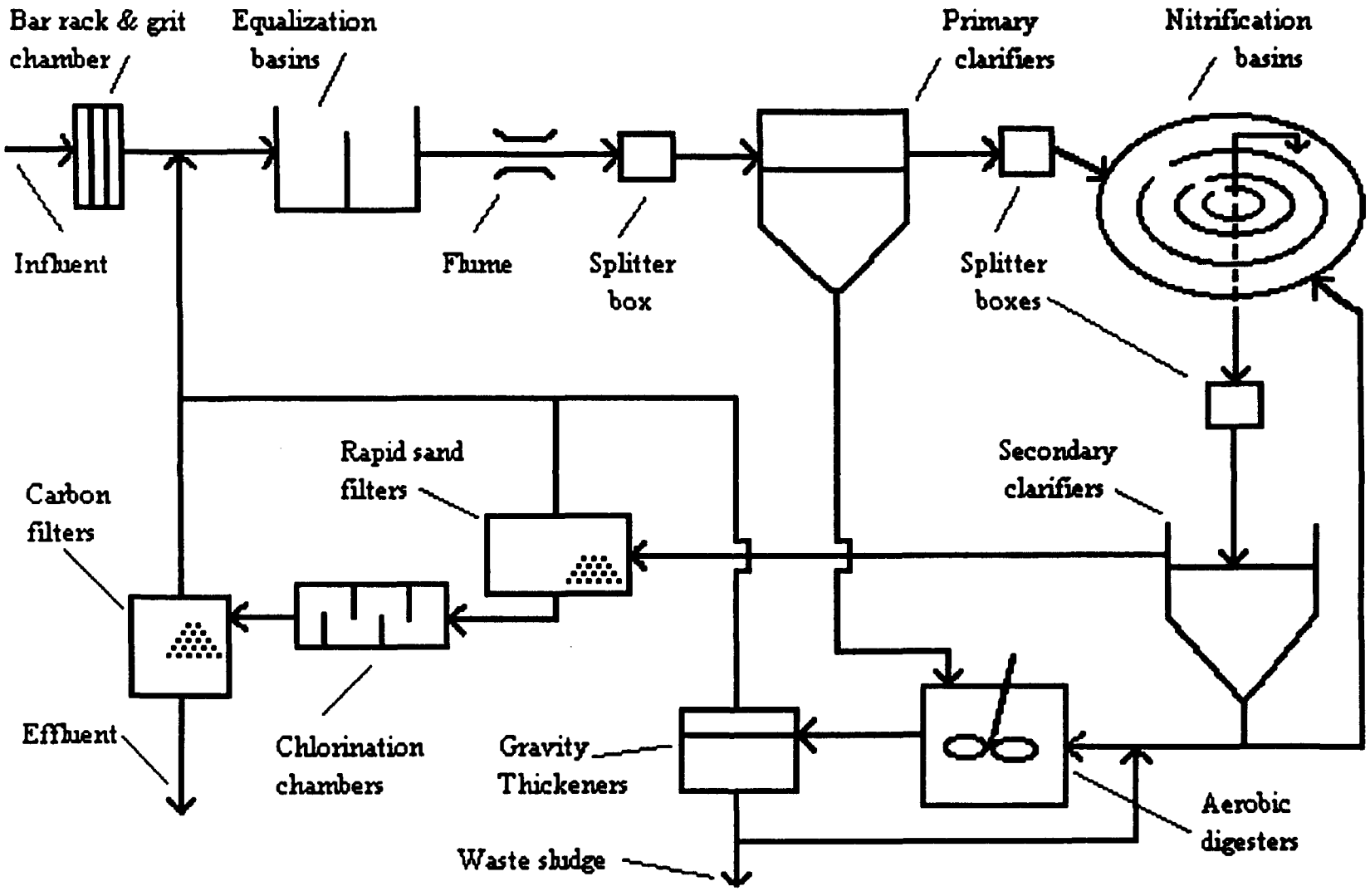
The Yellow River/Sweetwater Creek Water Reclamation Facility located in Gwinnett County, GA was designed to treat 12 MGD in achieving the most stringent of state effluent standards as shown below in the table below:

Table 2.1 - Permitted Effluent Standards

EFFLUENT STANDARD	PERMITTED MAX VALUE
Flowrate	12.0 MGD
Biochemical Oxygen Demand (BOD)	5 mg/L
Total Suspended Solids (TSS)	10 mg/L
Ammonia (NH_3)	1.0 mg/L
Nitrate (NO_3^-)	6.0 mg/L
Total Phosphorus	0.5 mg/L
Dissolved Oxygen (DO)	6.0 mg/L
Fecal Coliforms	2.5/100 mL
pH	6-8.5
Chlorine (Cl_2)	0.05 mg/L
Chemical Oxygen Demand (COD)	20 mg/L
Total Organic Carbon (TOC)	10 mg/L

The flow of the wastewater described below is also shown in the plant schematic (figure 2.4). The waste stream enters the plant through a bar rack and grit chamber to remove coarse debris and inorganic, non-flocculent solids. The influent pump station

PLANT SCHEMATIC - FIGURE 2.4



sends the wastewater to the head of the plant which begins with a set of equalization basins. Due to the loss of BOD in holding the wastewater for any length of time and odor problems, the basins are by-passed. The flow is measured with a Parshall flume and travels through a rapid mix splitter box where lime is added. Lime (typically between 2000-3000 lbs/day) is used to maintain pH and alkalinity. At this point, the plant becomes a mirrored operation; an east and west treatment process. Each side has a set of primary clarifiers designed to remove 70-80% of the organic matter and phosphorus with settled sludge and scum being pumped to aerobic digesters for processing. However, like the equalization basins, the primary clarifiers are inactive and, as a result, the wastestream is by-passed to the nitrification basins after passing through a Parshall flume.

The three-ring, oval nitrification basins are used as an activated sludge process to reduce organic waste. The design intent of this orbal system was primarily nitrification, but has been modified due to the by-passing of the primary clarifiers. The wastestream enters the outer most ring (compartment A) and is passed to the middle ring (compartment B). After flowing around the middle ring, the waste is transferred to the innermost ring (compartment C). In the center of compartment C is an outfall where alum is added. The wastestream flows to a splitter box where it is distributed to the secondary clarifiers. A percentage of this flow from compartment C may also be pumped back to compartment A. This recirculation to compartment A is not used if NH_4^+ levels

are elevated. Each nitrification basin has two 1400 hp pumps capable of recirculating 1600 gal/min or 4.61 MGD. Aeration disks in each compartment are varied to achieve the desired dissolved oxygen content. It is in this circular basin series in which nitrification (conversion of ammonia to nitrite to nitrate) and denitrification (nitrate reduction to nitrogen gas) occurs. Compartment capacities and sample retention times for the nitrification basins are shown in table 2.2 below:

Table 2.2 - Nitrification Basin Compartment Capacity

COMPARTMENT	CAPACITY (10^6 gal)	PERCENT OF TOTAL VOLUME (%)	RETENTION TIME (HR) IF TOTAL FLOW = 8 MGD
A	0.67	48	2.0
B	0.46	33	1.4
C	0.27	19	0.8
TOTAL	1.40	100	4.2

Solids concentrated in the secondary clarifiers are either returned to the nitrification basin or are wasted to the sludge thickener. Return sludge rates on experimentation days for this SRP ranged from 4.21 to 4.90 MGD while wastage rates ranged between 150,000 and 230,000 gal/day. The supernatant from the secondary clarifiers enters dual media filters which remove remaining suspended solids. The stream then enters a chlorine contact chamber, flows through an activated carbon filter and effluent flow meter prior to discharge into the Yellow River. Backwash water from the carbon and dual media filters return to the splitter box

before the equalization basins.

Solids treatment is completed in an aerobic digester and gravity thickener. Underflow from the gravity thickener is returned to the digester and the supernatant is returned to the head of the plant. Capacities for various treatment units are shown in the following table:

Table 2.3 - Treatment Unit Capacity

UNIT	NO. OF UNITS	CAPACITY/UNIT (MG)
Primary Clarifiers	4*	0.528
Nitrification Basins	4**	1.40
East Secondary Clarifiers	4	0.383
West Secondary Clarifiers	2***	0.995
East Gravity Thickener	1	0.316
West Gravity Thickener	1*	0.528
Dual Media Filters	8	0.0264
Carbon Filters	4	0.0586

Notes: (1) * Unit(s) not in service

(2) ** Three units in service

(3) *** Only one unit in service

In order to meet effluent limits and maximize plant efficiency, indicators are established by the plant manager and monitored by the plant operators. Efforts are made by plant operators to maintain the target values. During the experimentation period for this SRP, the indicators listed in the table below were established and monitored by plant management:

Table 2.4 - Plant Target Indicators

LOCATION	INDICATOR	TARGET
Splitter box (before Nitrification basin)	Alum Addition	800 mL/min
Nitrification basin (Comp A)	Dissolved Oxygen	0.4 mg/L
Nitrification basin (Comp C)	Dissolved Oxygen	2.5 mg/L
Nitrification basin (Comp C)	pH	6.7
Secondary clarifier	Mean Cell Residence Time (MCRT)	10 days
Secondary clarifier	Sludge Volume Index (SVI)	45-74 mL/g
Secondary clarifier	Depth of blanket	2 ft
Secondary clarifier	Waste Rate	250,000 GPD
Chlorination chamber	Chlorine residual	1.2 mg/L
Effluent	Chlorine residual	0.03 mg/L

2.22 PLANT PHOSPHORUS REMOVAL

The plant was designed to meet phosphorus limits by chemical precipitation through the addition of aluminum or iron salts prior to the primary clarifiers. However, since the primary clarifiers are by-passed, the chemical precipitation of phosphorus is accomplished in the secondary clarifiers. Alum in the form of $Al_2(SO_4)_3 \cdot 14H_2O$ which is stored as a bulk slurry is added at the outfall of the innermost nitrification basin compartment. After mixing, the wastestream enters the secondary clarifier where metal-phosphate complexes and other solids settle. Monthly averages for total phosphorus values and alum addition during the experimentation period of this SRP taken from daily plant records

are shown in the table below:

Table 2.5 - Monthly Phosphorus, Alum and BOD_5 Average Values

MONTH	INFLUENT BOD_5 (mg/L)	INFLUENT TOTAL P (mg/L)	EFFLUENT TOTAL P (mg/L)	ALUM ADDED (gal/d)	MASS AL ADDED (kg/d)
JAN	205	8.1	0.16	303	67.6
FEB	163	5.8	0.33	420	93.7
MAR	171	5.8	0.31	542	121
APR	194	6.1	0.34	551	123
AVG	183	6.5	0.29	454	101

To calculate the mass of aluminum, an alum content of 48.5% in the slurry and an alum density of 83 lb/ft^3 or 5.03 kg/gal (Metcalf & Eddy, 1990). The mass aluminum was subsequently determined by multiplying the alum content, alum density and molar fraction of aluminum.

Based on the average mass of aluminum added during the four month period of this SRP and by using the stoichiometric dosage of one mole of aluminum added per one mole of phosphorus removed, the approximate theoretical chemical phosphorus removal rate was calculated to be 3.1 mg/L. However, typical alum addition to phosphorus removal ratios are 2:1 (Sedlak, 1991). Therefore, chemical removal of phosphorus may be as low as 1.5 mg/L at the Yellow River Sweetwater Creek Facility.

Effluent from the secondary clarifier may be further polished for phosphorus when passing through the sand and carbon filters. However, the trapped phosphorus would not be removed from the

plant, since filtration backwash is returned to the head of the plant.

Theoretically, if the nitrification basin was used for enhanced BPR, PO_4-P release should occur in the anaerobic environment created in compartment A. The luxury uptake of phosphorus would then occur in compartments B and C of the basin. In most cases, anaerobic contact times for biological phosphorus removal systems are between one and two hours (Sedlak, 1991). As shown on table 2.2, the retention time in compartment A is 2.0 hours for an 8 MGD flow, which allows sufficient anaerobic contact time. The anaerobic detention time would vary due to recycle flow rates and use of the aeration disks, in addition to the influent flow rate. As a result, compartment A would not solely be an anaerobic zone, but a series of environments including aerobic and anoxic zones.

One of the most important factors that affect the amenability of wastewater to biological phosphorus removal is the ratio of influent BOD_5 to total phosphorus. Research indicates that for plants with BOD_5 to total phosphorus ratio less than 20, it may be difficult to achieve an effluent total phosphorus level of 1.0 to 2.0 mg/L (Sedlak, 1991). Using the average values in figure 2.5, the BOD_5 to total phosphorus ratio is 28, which is within the acceptable range for biological phosphorus removal.

CHAPTER 3
EXPERIMENTAL APPROACHES

3.1 ANALYTICAL METHODS

3.11 CHEMICAL OXYGEN DEMAND (COD)

A. SUMMARY OF METHOD: In the COD test, the sample is heated using potassium dichromate, a strong oxidizing agent. Oxidizable organic compounds react, reducing the dichromate ion ($Cr_2O_7^{2-}$) to the chromic ion (Cr^{3+}). COD is determined by colorimetrically measuring either the amount of dichromate remaining or the amount of chromic ion produced. The COD reagent also contains silver ions acting as catalysts and mercury ions which prevent interferences from chloride.

B. INSTRUMENT DESCRIPTION: A Hach DR/2000 Laboratory Spectrophotometer is used to measure $Cr^{+3}/Cr_2O_7^{2-}$and thereby, COD.

C. PROCEDURES: The total COD and soluble COD tests are completed in accordance with Standard Methods (1989).

D. QUALITY CONTROL: To ensure accuracy, a standard solution (prepared in accordance with Chapter 3.31) is tested with each pilot study. The 500 mg/L standard for COD is prepared by dissolving 424 mg of potassium acid phthalate and diluting to one liter with deionized water. Environmental Resource Associates (ERA) quality control samples are also utilized to ensure precision of the spectrophotometer. Additionally, at least one duplicate sample and one spiked sample is prepared and analyzed for every ten samples. The 12 ppm spike sample is prepared by adding 2 mL of a 300 mg/L ERA stock solution to 50 mL of sample.

3.12 DETERMINATION OF ANIONS BY ION CHROMATOGRAPHY

A. SUMMARY OF METHOD: A sample is injected into a stream of sodium bicarbonate eluent (1.8mM Na_2CO_3) and is passed through a series of ion exchangers. The anions chloride, fluoride, nitrate-N, nitrite-N, orthophosphate-P and sulfate are separated based on their relative affinities for a low capacity, strongly basic anion exchanger (guard and separator columns). The separated anions are directed through a micromembrane suppressor which is continuously regenerated using a strong acid solution (0.025N H_2SO_4) acting as the cation exchanger. In the suppressor, the separated anions are converted to their highly conductive acid forms and the carbonate eluent becomes a weakly conductive carbonic acid. The anion acid compounds are measured by conductivity and identified on the basis of retention time as compared to standards. Measurement of area beneath each peak quantifies the amount of each anion.

B. INSTRUMENT DESCRIPTION: A Dionex 2000i Ion Chromatograph with an HPIC-AS4A column is used to measure ion quantity.

C. REAGENT PREPARATION:

1. The eluent solution is prepared by dissolving 1.008 g sodium carbonate and 1.018 g of sodium bicarbonate in reagent water and diluting to 4 L.

2. The regeneration solution is prepared by diluting 2.8 ml of sulfuric acid to 4 liters with reagent water.

3. A 1000 mg/L stock standard solution is prepared for each anion by dissolving the following chemicals in reagent (deionized) water and diluting to 1 L in a glass flask:

a. Cl^- using NaCl: 58.44 / 35.45 = 1.65 g NaCl

b. F^- using KF: 58.10 / 19.00 = 3.06 g KF

c. NO_3^--N using KNO_3: 101.1 / 14.01 = 7.22 g KNO_3

d. NO_2^--N using KNO_2: 85.11 / 14.01 = 6.07 g KNO_2

e. PO_4^{-3}-P using K_2HPO_4: 174.2 / 30.97 = 5.62 g K_2HPO_4 or KH_2PO_4: 136.1 / 30.97 = 4.39 g K_2HPO_4

f. SO_4^{-2} using K_2SO_4: 174.3 / 96.06 = 1.81 g K_2HPO_4

Stock standard solutions are stored at 4°C and prepared weekly. Nitrite and phosphate solutions are prepared daily.

D. PROCEDURES: The samples are analyzed in accordance with with EPA and Standard Methods (1989). Specific procedures for the Dionex 2000i Ion Chromatograph are summarized as follows:

1. The ion chromatograph is turned on and allowed to reach equilibrium after confirming the eluent flow rate at approximately 2 mL/min. The regeneration flowrate is maintained at approximately 3 mL/min.

2. The system is calibrated by injecting four concentrations of the stock standard solution (prepared in accordance with Chapter 3.32) for each ion in order to develop a calibration curve. New calibration curves are prepared on each day of testing or upon addition of new reagent or eluent whichever occurs first. The ranges selected for the points on the curve are based on expected values of the respective anion during the sampling event or pilot study. As an example, the concentrations selected for the anion calibration of Pilot Study 5 are shown in table 3.1. From the points in table 3.1, the ion chromatograph

Table 3.1 - Ion Chromatograph Calibration Points - Pilot Study 5

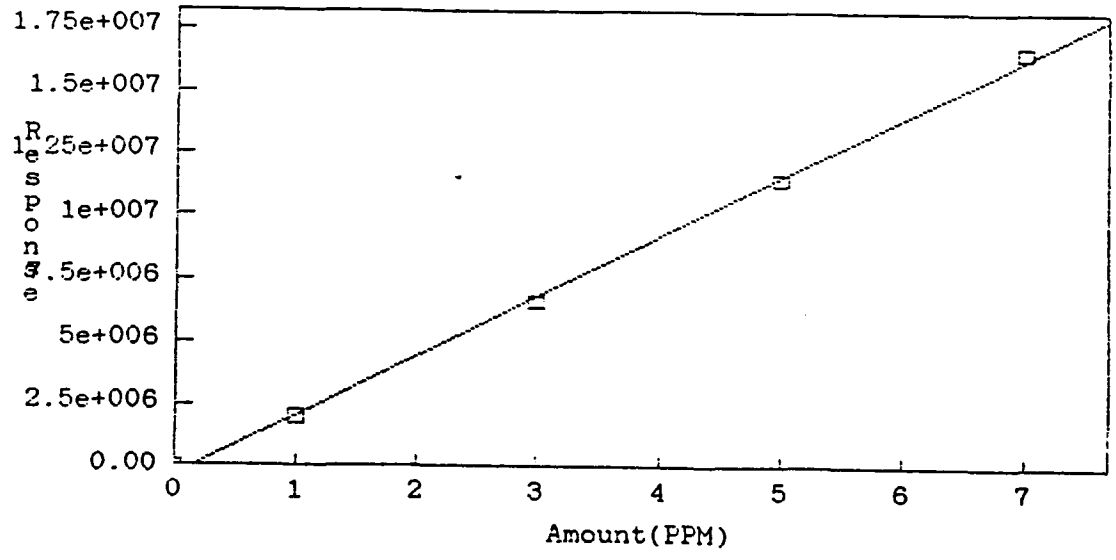
	POINT NUMBER (mg/L)				
ANION	1	2	3	4	5
Cl^-	0	5	10	15	20
F^-	0	2	4	6	8
NO_3^-	0	1	2	3	4
NO_2^-	0	1	2	3	4
PO_4^-	0	1	3	5	7
SO_4^-	0	5	10	20	20

generates a calibration curve for each anion based on response. As an example, the PO_4-P curve for Pilot Study 5 is shown in figure 3.1:

Figure 3.1 - PO_4-P Calibration Curve for Pilot Study 5

Method: C:\DX\METHOD\ANION.MET

Component: PHOSPHATE
Fit Type: Linear
r^2: 0.998590
Amt = Resp * 4.205e-007 + 0.1252
Resp = Amt * 2.378e+006 + -2.978e+005
Standardization: External
Calibration: Height



2. All samples are placed in 5 mL plastic vials and passed through a 0.45 micron filter into the ion chromatograph. Anion results are provided by the ion chromatograph for each individual sample. Figure 3.2 on the following page shows the results from a Pilot Study 6 sample.

E. \LITY CONTROL: To ensure accuracy, a spike, blank and duplica.. is run every ten samples. For Pilot Studies 1 and 2, spikes for PO_4-P in the amount of 2 mg/L were prepared by diluting 10 mL of the standard stock solution with 90 mL of deionized water to form a 100 mg/L solution of PO_4-P. One mL of the 100 mg/L solution was mixed with 49 mL of deionized water to produce a 2 mg/L PO_4-P solution. One mL of this solution was added to the 5 mL sample drawn for analysis. Due the multiple dilutions and small transfer volumes, poor recovery rates were observed. As a result, for Pilot Studies 3-13, a larger sample (50 mL) is drawn for spikes and recovery improved. In Pilot Studies 3-7, one mL of 100 ppm PO_4-P solution is added to the 50 mL sample which produces a 2 ppm spike. In Pilot Studies 8-13, one mL of the standard stock solution (10,000 mg/L) was added to the 50 mL sample to produce a 20 mg/L spike.

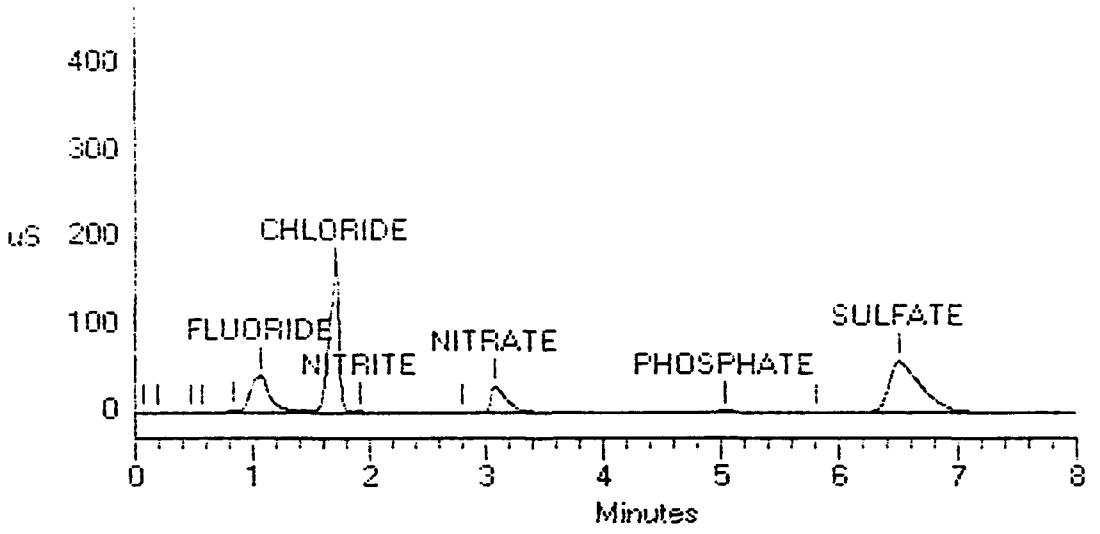
Figure 3.2 - Ion Chromatograph Data Sheet for Pilot Study 6

```
Sample Name: 1C                                   Date: Mon Apr 06 19:51:43 1992
Data File  : C:\DX\DATA\BOLIV001.D02
Method     : C:\DX\METHOD\ANION.met
ACI Address: 1       System : 1       Inject#:   2  Detector: CDM-2
```

REPORT	VOLUME	DILUTION	POINTS	RATE	START	STOP	AREA REJ
External	1	1	2400	5Hz	0.00	8.00	1000

Pk. Num	Ret Time	Component Name	Concentration PPM	Height	Area	Bl. Code	%Delta
6	1.07	FLUORIDE	4.397	41036235	491623125	2	6.67
7	1.70	CHLORIDE	22.620	157902474	975864779	3	6.25
8	1.92	NITRITE	0.021	1152662	8620310	4	1.77
10	3.08	NITRATE	3.616	29566444	272093439	2	-0.54
11	5.03	PHOSPHATE	0.503	898245	13055685	3	-0.92
13	6.50	SULFATE	14.519	57711659	1072895600	1	2.04
		Totals	45.676	288266720	2834152939		

File: C:\DX\DATA\BOLIV001.D02 Sample: 1C



3.13 PHOSPHORUS (COLORIMETRIC)

A. SUMMARY OF METHOD: Analysis for total phosphorus is generally a two step process: (1) conversion of phosphorus to PO_4-P and (2) colorimetric determination of PO_4-P. By omitting step 1, PO_4-P is isolated and can be analyzed independently from other forms of phosphorus. In conducting total phosphorus analysis, peroxydisulfate is used in the digestion process which is necessary to convert phosphorus to its ortho- form. For both total phosphorus and PO_4-P analyses, ammonium molybdate and antimony tartrate are added to the sample in an acid medium. With the presence of phosphorus, antimony-phosphorus complexes are formed. These complexes are reduced to an intensely blue-colored complex by ascorbic acid. The color is proportional to the phosphorus concentration.

B. INSTRUMENT DESCRIPTION: The spectrophotometer used is a Milton Roy Spectronic 601 which has a light path of 1 cm and is suitable for measurements at 650 and 880 nm.

C. PROCEDURES: The total phosphorus tests are completed in accordance with Standard Methods (1989) (III-Persulfate Digestion Method and Ascorbic Acid Method). The PO_4-P tests are also completed in accordance with Standard Methods (1989). Specific procedures using the Milton Roy Spectronic 601 are summarized below:

1. A calibration curve is developed by reading the percent transmittance of five samples with concentrations of 0, 0.1, 0.3, 0.7 and 1.0 mg/L of PO_4-P, respectively.

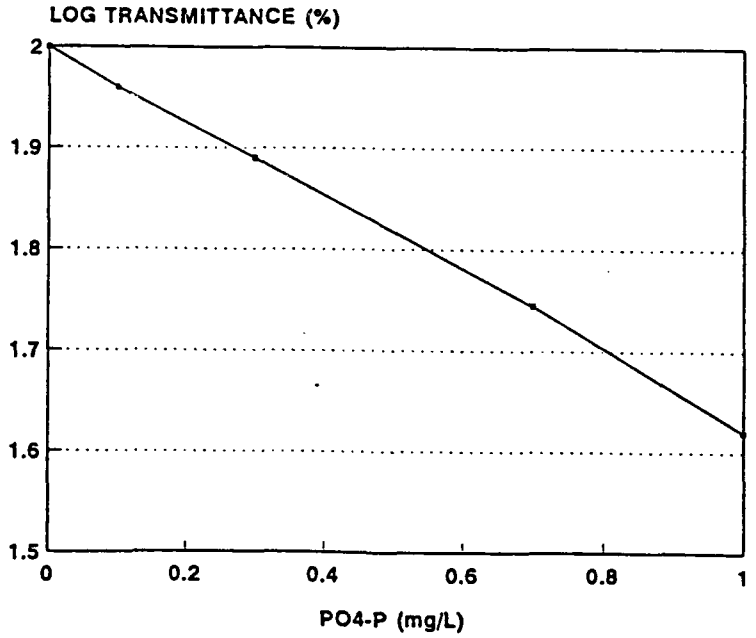
2. For the five points, concentration PO_4-P versus the log percent transmittance are plotted.

3. 50 mL samples from sampling events and pilot studies are analyzed for percent transmittance and the resulting concentration is recorded from the calibration curve. Samples with concentrations expected to be greater than 1.0 mg/L are diluted to levels between 0 and 1.0 mg/L. Pilot Study calibration samples and curve are shown in table 3.2 and figure 3.3.

Table 3.2 - Colorimetric PO_4 Calibration Samples for Pilot Study 7

SAMPLE	% TRANSMITTANCE
Blank	100
0.1 mg/L	91.7
0.3 mg/L	77.5
0.7 mg/L	55.6
1.0 mg/L	42.1

Figure 3.3 - Log Transmittance vs PO_4-P for Pilot Study 7



Actual values for Pilot Study 7 are subsequently presented in table 3.3.

Table 3.3 - Colorimetric PO_4-P Samples for Pilot Study 7

A. REACTOR & SAMPLE #	B. %TRANS-MITTANCE	C. DILUTION FACTOR	D. PO_4-P (mg/L)	E. PO_4-P ACTUAL (mg/L) (C X D)
A1	79.1	1	0.28	0.28
A2	69.1	1	0.44	0.44
A3	70.1	1	0.42	0.42
A4	54.0	1	0.72	0.72
A5	50.7	50/10 x 50/25	0.80	8.0
A6	74.9	50/10 x 50/10	0.35	8.8
A7	66.3	50/2 x 50/20	0.48	30
A8	64.9	50/2 x 50/20	0.51	32
A9	60.5	50/2 x 50/20	0.59	37
A10	58.2	50/2 x 50/20	0.63	39
A11	60.4	50/2 x 50/20	0.59	37
B1	79.1	1	0.28	0.28
B2	92.6	1	0.10	0.10
B3	64.0	50/20	0.53	1.3
B4	64.1	50/10	0.52	2.6
B5	59.6	50/10 x 50/20	0.61	7.6
B6	56.7	50/10 x 50/20	0.67	8.4
B7	56.4	50/2	0.67	17
B8	70.6	50/2 x 50/20	0.41	26
Low Control	82.5	1	0.23	0.23
Hi Control	47.6	1	0.88	0.88

The dilution factor shown in column C of the table above, is based on the 50 mL sample. A dilution factor of "1" would indicate the

sample analyzed was not diluted. A dilution factor of "50/20" denotes that 20 mL of the reactor sample was used with 30 mL of deionized water. A dilution factor of "50/10 x 50/20" would mean that (1) a solution of 10 mL of reactor sample was mixed with 40 mL of deionized water and (2) 20 mL of this solution was diluted further with 30 mL of deionized water.

D. QUALITY CONTROL: The development of the calibration curve from stock solution for each sampling event and pilot study ensures accuracy. Additionally, high and low range ERA quality control samples are analyzed during each experiment to ensure accuracy.

3.14 OTHER ANALYTICAL METHODS

pH - Orion Model 520A meters are used to measure pH of samples and probes are stored in buffer solution during non-use. The pH meters are operated in accordance with Standard Methods (1989).

DISSOLVED OXYGEN (DO) - The DO content is measured using YSI Model 59 Dissolved Oxygen Meters in which the calibration is confirmed daily using the Winkler Titration Method.

TOTAL SUSPENDED SOLIDS (TSS) - TSS are determined in accordance with Standard Methods (1989).

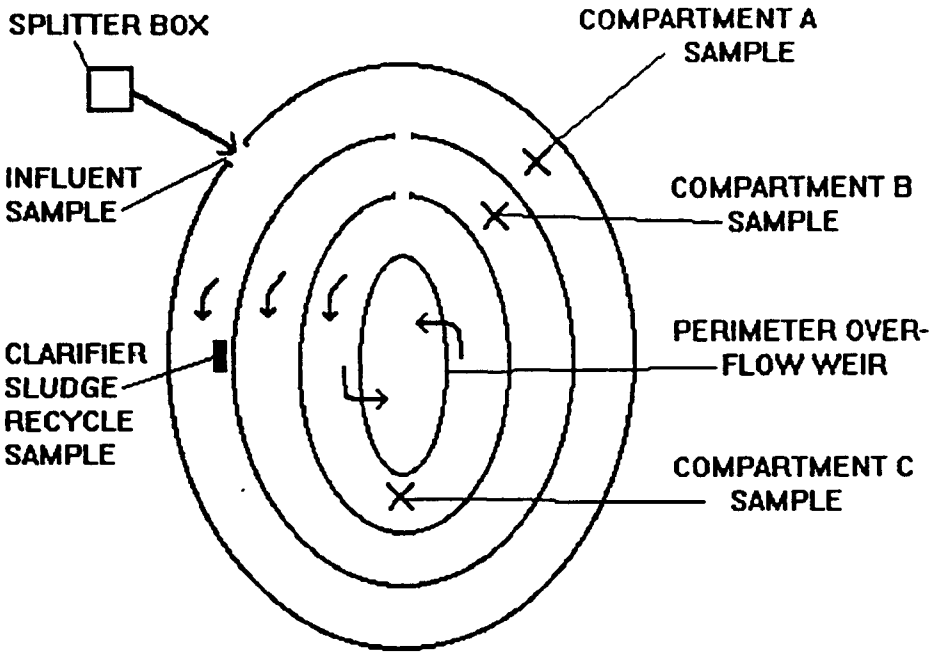
3.2 EXPERIMENTAL APPARATUS

All laboratory analysis was completed in the Gwinnett County Laboratory Services located on the grounds of the Yellow River Sweetwater Creek Water Reclamation Facility. The facility is third party accredited by the American Association for Laboratory Accreditation. Standard set-up, operation, sampling, equipment and sample calculations for sampling events and pilot studies are summarized in the following pages. Details unique to a specific pilot study are described in Chapter 4.2.

3.21 Sampling Events

Sampling Events were a joint effort with Mr. Greg Dyson, also an environmental engineering graduate student. All samples were taken manually using a plastic bailer. Use of an ENCO automatic sampler was discontinued due to clogging of the inlet with debris in the nitrification basin. Samples were immediately transferred to glass bottles and stored at 4° C until analyzed. At the time of sampling, plant influent, plant effluent and east side plant influent were recorded to determine mass loading. In Sampling Events 1 and 2, samples were tested for PO_4-P, NO_3^-, NO_2^- and total COD. Total phosphorus was also determined in Sampling Event 2. In Sampling Event 3, samples were only analyzed for PO_4-P. Sample locations from the nitrification basin are shown below:

FIGURE 3.4 - SAMPLING POINTS (BASIN 1)



The following is a list of equipment used in the sampling events:

Table 3.4 - Sampling Events Equipment List

ITEM	PURPOSE
Plastic bailer	Draw plant sample
Glass bottles (500 mL)	Store sample
Blender	Homogenize sample for COD test
Plastic vials (5 mL)	Ion testing
Pipettes	Draw samples

3.22 Pilot Studies

The pilot studies were conducted under a laboratory exhaust hood in a location convenient for both reagent preparation and sample analysis. Beakers (3,000 mL) placed on magnetic stirring

plates acted as batch reactors in the pilot studies.

A small air compressor provided oxygen for aerobic reactors and compressed nitrogen was fed into reactors requiring an anaerobic environment. Gasses were fed via 1/2 inch plastic tubing with a 20 micron diffuser to distribute the respective gas within the reactor and magnetic stirring rods kept the reactors well-mixed during the study. A standard gas flow for both air and nitrogen of 1.75 L/min was maintained by setting the flowmeter (rotometer) at 80. See Appendix A for gas flow rate calculations.

At the start of each pilot study, the total influent and east side flows instantaneous flowrates were recorded from the plant flow meters. The daily values for waste and return sludge rates and total alum added were recorded from the plant operators log. A summary of all rates recorded for Pilot Studies 1 through 13 are shown in table 3.5.

Raw waste samples for the pilot studies are drawn from the head of the plant. Mixed liquor (ML) samples for the pilot studies are drawn from the secondary clarifier influent splitter box on the east side of the plant. Samples taken from this location are representative of mixed liquor at the completion of the activated sludge process. Mixed liquor was prepared for experimentation as shown in table 3.6. The adjustments shown above were made to increase the ML concentration and thus, increase the TSS, microbial population and PO_4-P. After removing supernatant (Pilot Studies 3-13), the remaining ML was well-mixed prior to distribution to the reactor(s).

Table 3.5 - Plant Flowrates

PILOT STUDY	INFLUENT FLOW (MGD) TOTAL	INFLUENT FLOW (MGD) EAST SIDE	WASTE SLUDGE-EAST (GPD)	RETURN SLUDGE-EAST (MGD)	ALUM ADDED TOTAL (GAL)
1	13.8	10.0	230,000	4.31	455
2	17.5	14.5	190,000	4.39	618
3	15.4	12.2	190,000	4.42	536
4	13.1	10.2	180,000	4.36	471
5	12.2	9.5	180,000	4.90	488
6	10.0	7.4	145,000	4.81	520
7	8.5	6.4	150,000	4.72	552
8	10.0	7.7	150,000	4.70	520
9	9.8	7.4	170,000	4.61	569
10	9.5	7.3	170,000	4.37	731
11	13.0	10.0	170,000	4.21	731
12	6.4	5.3	160,000	4.47	536
13	12.8	8.7	160,000	4.35	504

Table 3.6 - Mixed Liquor (ML) Preparation

PILOT STUDY	INITIAL ML SAMPLE (L)	SETTLING TIME (min)	SUPERNATANT REMOVED (L)
1-2	12	0	0
3-8	17	15	5
9-13	12	15	9

For studies using aerobic and anaerobic reactors after Pilot Study 1, it was determined that maintaining a pH similar to plant conditions would be advantageous. As a result, a buffer of 350

mg/L of sodium bicarbonate ($NaHCO_3$) was used in order to raise the alkalinity by 200 mg/L as carbonate ($CaCO_3$).

In Pilot Studies 2, 3, 4, and 6, acetate was added in varying quantities from 250 to 750 mg/L to provide additional substrate for microbial growth. In addition to acetic acid, phenol, dextrose and glucosamine were added in Pilot Studies 8-10, 12 and 13 to provide an ample variety of readily available substrate for growth. Dextrose and glucosamine were dissolved in the acetic acid solution in addition to the phenol which was also mixed in the substrate solution.

In order to maximize growth potential in Pilot Studies 8-13, the essential nutrients, nitrogen and phosphorus were added in the form of ammonium chloride (NH_4Cl) and potassium phosphate (KH_2PO_4), respectively. Typical additions were 40 mg/L of nitrogen and 50 mg/L of phosphorus.

Sample calculations for buffer, substrate and nutrient additions are shown in Appendix A.

The following table is a summary of the equipment used and its purpose in the pilot studies:

Table 3.7 - Pilot Study Equipment List

ITEM	PURPOSE
Plastic bucket (12 L)	Draw mixed liquor sample
Beakers (2000 mL)	Draw off supernatant
Beakers (3000 mL)	Reactor
Erlenmeyer flasks (250, 500 and 1000 mL)	Gas flow rate measurements
Pipettes	Transfer samples
Burette	Titration
Magnetic plate	Reactor mixing
Magnetic bar	Reactor mixing
Parafilm	Maintain reactor environment
Air pump	Aerobic environment
Compressed nitrogen	Anaerobic environment
Plastic tubing (1/2")	Transport air and nitrogen
Diffuser (20 micron)	Distribute air and nitrogen with the reactor
Rotometer	Gas flow rate
Plastic vials (5 mL)	Ion testing
Chemical stands	Secure burette and probes

CHAPTER 4
DATA ANALYSIS AND DISCUSSION

4.1 SAMPLING EVENT AND PILOT STUDY OVERVIEW

The sampling events and pilot studies were conducted in numerical sequence in accordance with the detailed protocol described in Chapters 3.21 and 3.22, respectively. Graphs of data accumulated during each experiment are shown in each event or study summary. The data are also shown in table format in Appendix B. In many cases, conclusions and observations of one experiment led to conditions in subsequent experiments.

The purpose of the sampling events was to observe conditions affecting chemical and biological phosphorus removal. The first two events focused on conditions in and around the nitrification basin, while the third sampling event isolated conditions around the secondary clarifier. Although Sampling Events 1 and 2 were similar in nature, pH and temperature were monitored in the second event. Observations in the first two sampling events led to the focus on the secondary clarifier in Sampling Event 3.

The purpose of the pilot studies was to subject plant mixed liquor to various conditions in an effort to encourage enhanced biological phosphorus release and uptake.

In Pilot Studies 1-4, 6 and 8-13, waste was subjected to anaerobic and aerobic environments to observe phosphorus release and uptake. During this sequence, various modifications were implemented in an effort to create an ideal environment for biological activity. The most important of these modifications are listed below:

(1) In an attempt to prevent sharp increases in pH due to stripping of carbon dioxide, a sodium bicarbonate buffer was used in experiments after the first pilot study.

(2) Existing substrate was supplemented by the addition of acetate as acetic acid in Pilot Studies 2-4 and by a combination of acetate, dextrose, glucosamine and phenol in Pilot Studies 8-13.

(3) Beginning in Pilot Study 3, the initial mixed liquor was thickened for experiments to increase the microbial seed population.

(4) Addition of phosphorus to promote uptake was utilized in Pilot Studies 9-13.

The amount of PO_4-P in solution throughout the range of pH values was determined in Pilot Studies 5 and 7. In these experiments, mixed liquor samples were titrated to low pHs with a strong acid and to high pHs with a strong base, while analyzing for PO_4-P at various pH increments. The purpose of the titration studies was to identify the amount of phosphorus available in solution at various pH values. By knowing the maximum amount of phosphorus available and total phosphorus a mixed liquor sample, the amount of phosphorus bound in microbial cells can then be calculated.

Chapters 4.2 and 4.3 summarize each sampling event and pilot study, respectively. Overall conclusions are provided in Chapter 4.4.

4.2 SAMPLING EVENTS 1-3

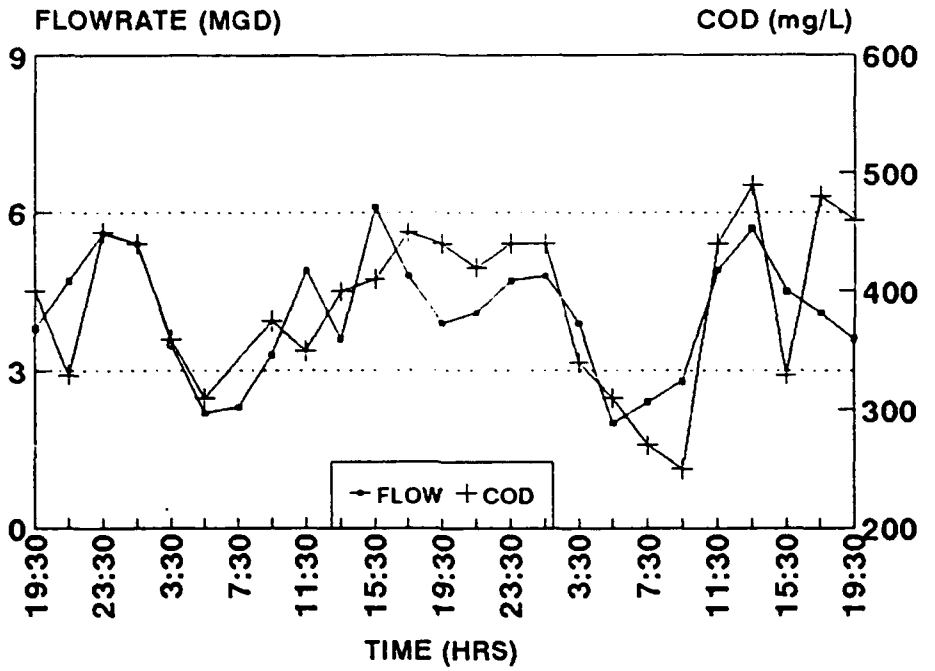
SAMPLING EVENT 1

The purpose of Sampling Event 1 was to observe levels of PO_4-P, NO_3^-, NO_2^- in each of three rings of the nitrification basin and underflow of the secondary clarifier. Samples were taken for a 48-hour period in accordance with the Sampling Event protocol summarized in Chapter 3.2.

Flowrates and COD in nitrification basin 3 fluctuated diurnally as shown in figure 4.1. The range for flowrates and COD were 2.2-6.1 MGD and 250-490 mg/L, respectively.

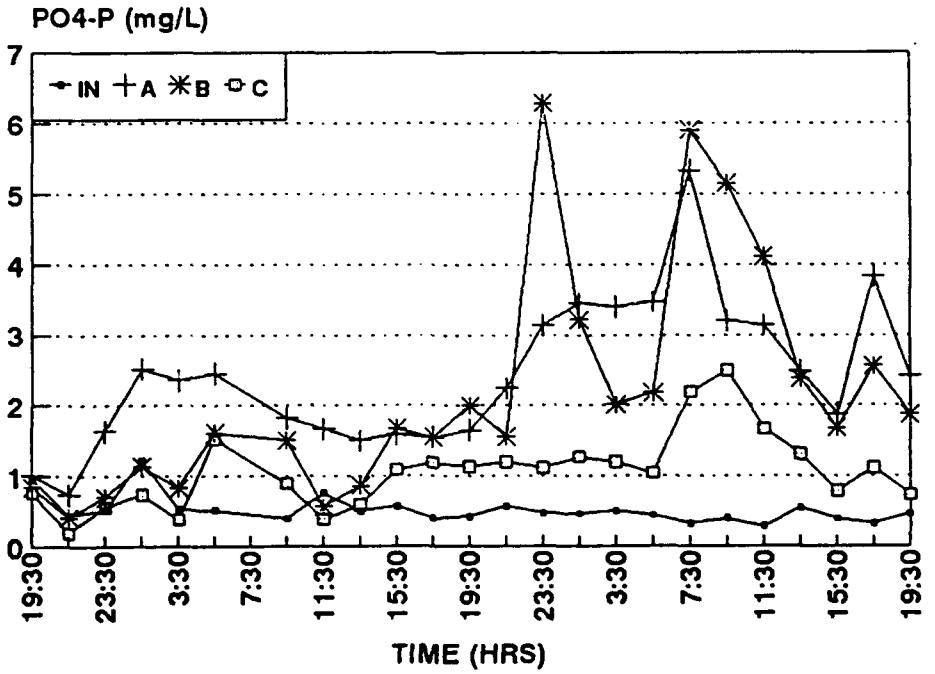
Soluble phosphorus (PO_4-P) levels in the nitrification basin influent, compartments A, B and C and the recycle underflow are shown in figures 4.2 and 4.3. Influent PO_4-P levels averaged 0.52 mg/L which is extremely low. Typical PO_4-P concentrations are 3 mg/L for weak untreated domestic wastewater and 5 mg/L for medium untreated wastewater (Metcalf and Eddy, 1991). PO_4-P levels doubled in compartments A and B between hours 26 and 36 of the experiment. PO_4-P levels in the recycle stream from the secondary clarifier were typically greater than 5 mg/L and ranged to 15.8 mg/L. High PO_4-P levels in compartment A may also be attributed to phosphorus from the secondary clarifier return in which the flowrate was approximately 4 MGD and average PO_4-P level was 6.64 mg/L during the sampling event. The three day values for return flowrate are shown in column three of table 4.1:

FIGURE 4.1 - SAMPLING EVENT 1
FLOWRATE AND COD VS TIME



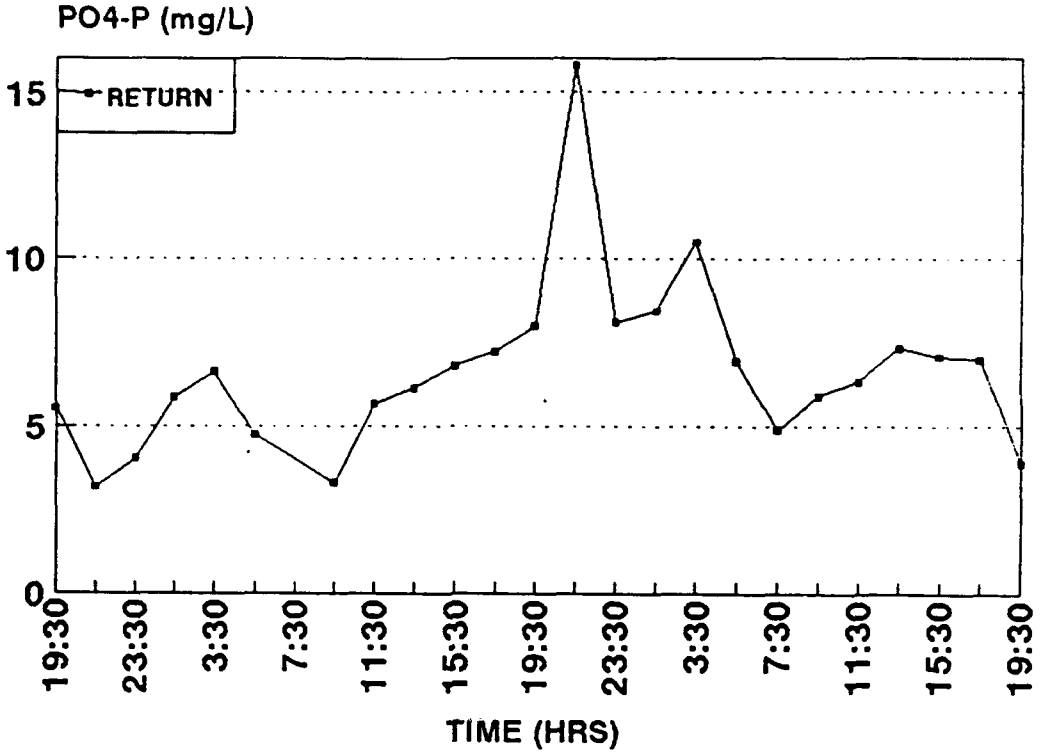
FLOWRATE AND COD AT INFLUENT TO ORBAL SYSTEM (BASIN 3)

FIGURE 4.2 - SAMPLING EVENT 1
PO4-P VS TIME



SAMPLE POINTS: ORBAL SYSTEM INFLUENT (IN), AND COMPARTMENTS A-C

FIGURE 4.3 - SAMPLING EVENT 1
PO4-P VS TIME



SAMPLE POINT: RETURN SLUDGE TO ORBAL SYSTEM

Table 4.1 - Other Plant Data for Sampling Event 1

DATE	WASTE SLUDGE (GPD)	RETURN SLUDGE (MGD)	ALUM ADDED (GPD)	NUMBER OF RECIRCULATION PUMPS (RING C TO RING A) IN OPERATION AND TIME
1/29	160,000	4.11	260	1 PUMP FROM 19:30 TO 24:00
1/30	170,000	4.10	211	1 PUMP FROM 00:00 TO 21:05 0 PUMP FROM 21:05 TO 24:00
1/31	170,000	3.85	244	0 PUMP FROM 00:00 TO 09:00 1 PUMP FROM 09:00 TO 18:00 2 PUMPS FROM 18:00 TO 19:30

During the period of 24 to 36 hours (19:30 to 07:30), no nitrate was detected in compartment A. However, during a majority

of the event, both nitrite and nitrate were detected in the influent which was unexpected, since typical values for weak through strong wastewater is zero (Metcalf and Eddy, 1991). Backwash from filter cleaning which is returned to the head of the plant may be the cause of nitrite and nitrate detection in the influent. Therefore, one can also conclude that there is fixed film biological activity occurring in the filter. The lack of nitrate in compartment A between hours 26 and 36 may have resulted in the high PO_4-P levels. Nitrate is also noticeably absent throughout the event (see Table 6.5 in Appendix B). With minimal aeration in compartment A and no nitrate, anaerobes can theoretically develop, thereby releasing phosphorus. If oxygen or nitrate (which would be a suitable substitute as an electron donor) is present, facultative microbes would develop aerobically; resulting in no release of PO_4-P (Sedlak, 1991).

In order to mass balance maximum phosphorus levels in the plant, it will be necessary to determine total phosphorus. Future sampling events should also include pH of the recycle and temperature of the samples in order to compare actual conditions with optimal biological phosphorus removal conditions.

SAMPLING EVENT 2

The purpose of Sampling Event 2 was to observe levels of PO_4-P, NO_3^-, NO_{2-} in each of three rings of the nitrification basin and underflow of the secondary clarifier. Samples were taken for a 48 hour period in accordance with the Sampling Event protocol summarized in Chapter 3.2.

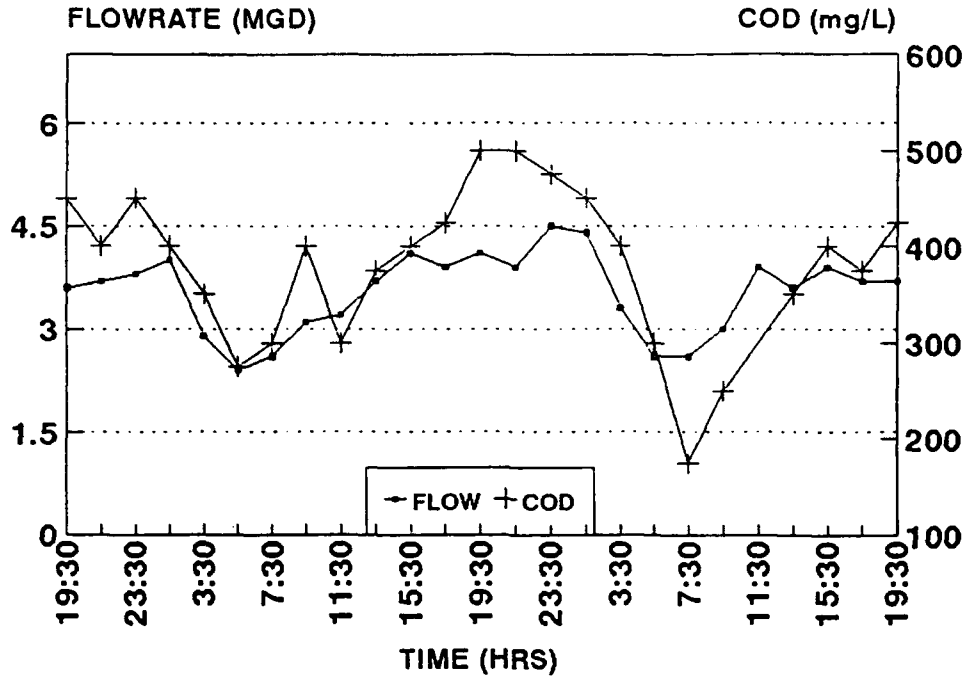
Flowrates and COD in basin 1 averaged 3.5 MGD and 380 mg/L, fluctuating diurnally as shown in figure 4.4. These values are comparable to Sampling Event 1.

Soluble phosphorus (PO_4-P) levels in the nitrification basin influent, compartments A, B and C are shown in figure 4.5, while total phosphorus and PO_4-P of the recycle underflow are shown in figure 4.6. Influent PO_4-P values were for the most part significantly lower than expected with only 10 of the 22 samples recording greater than 0 mg/L. Total phosphorus values for the sampling event varied between 2.3 and 9.1, averaging 4.8 mg/L. These values fall between the typical composition of "weak" and "medium" wastewater for total phosphorus which are 4 and 8 mg/L, respectively (Metcalf and Eddy, 1991). Surprisingly, PO_4-P levels in compartments B and C were negligible throughout the event. Understandably, PO_4-P levels in compartment A fluctuated similar to that of the return levels; however, the values were basically twice as low as observed in Sampling Event 1.

Nitrate was not observed in compartment A, but was found consistently throughout the sampling event in compartments B and C.

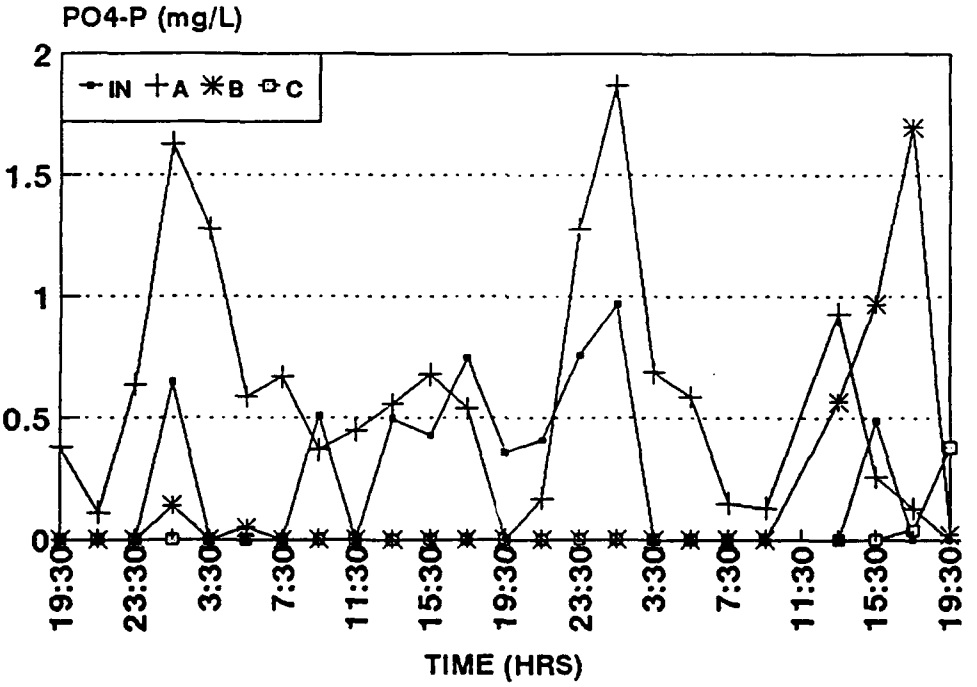
Influent and return pH values remained steady between 6.8-7.2

FIGURE 4.4 - SAMPLING EVENT 2
FLOWRATE AND COD VS TIME



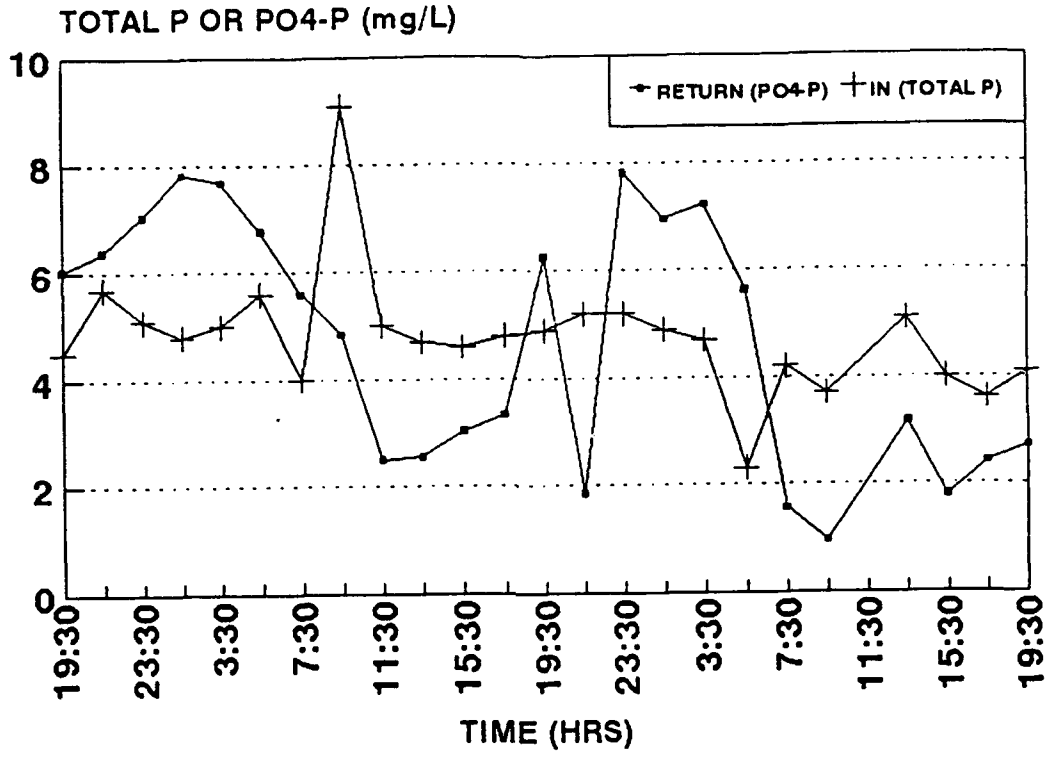
FLOWRATE AND COD AT INFLUENT TO ORBAL SYSTEM (BASIN 1)

FIGURE 4.5 - SAMPLING EVENT 2
PO4-P VS TIME



SAMPLE POINTS: ORBAL SYSTEM INFLUENT (IN) AND COMPARTMENTS A-C

FIGURE 4.6 - SAMPLING EVENT 2
PHOSPHORUS VS TIME



SAMPLE POINTS: ORBAL SYSTEM INFLUENT (TOTAL P) AND RETURN SLUDGE (PO4-P)

and 9-10, respectively while temperatures remained steady for both locations between 15-16°C. It has been shown that the specific phosphorus release rates for a batch activated sludge sample increased by a factor of 5 as the temperature increased from 10°C to 30°C (Shapiro *et al.*, 1967). The average pH levels of the recycle wastestream was 7.1, while the plant target value for compartment C of the nitrification basin is 6.7. Studies have shown that pH levels between 6.5 and 7.0 had little effect on phosphorus uptake in the aerobic zone (Tracy and Flammino, 1985). Therefore, pH as well as temperature are suitable for biological

phosphorus removal.

PO_4-P was not observed in compartment A despite the lack of nitrate. A possible explanation is that oxygen was available in compartment A resulting in aerobic activity and therefore, no release of phosphorus. With the operation of two recirculation pumps (as shown in column 5 of table 4.2), for a majority of the sampling event approximately 4.6 MGD of well-aerated mixed liquor is recycled to compartment A which would double the influent flowrate dissolved oxygen content in the basin.

Table 4.2 - Other Plant Data for Sampling Event 2

DATE	WASTE SLUDGE (GPD)	RETURN SLUDGE (MGD)	ALUM ADDED (MGD)	RECIR PUMPS FROM RING C TO RING A IN OPERATION
2/19	180,000	4.32	374	2 PUMPS
2/20	180,000	4.44	536	2 PUMPS
2/21	180,000	4.35	504	2 PUMPS UNTIL 0230 0 PUMPS UNTIL 1300 2 PUMPS UNTIL 1930

As in Sampling Event 1, the recycle PO_4-P values were up to 6 times greater than values in compartment C. An analysis of phosphorus levels around the secondary clarifier demonstrates that anaerobic activity is evident in the clarifier. PO_4-P levels in the influent were essentially zero while the recycle quantity averaged 4.66 mg/L PO_4-P and the clarifier overflow (effluent) sample yielded 1.9 mg/L total phosphorus. Sampling Event 3 should provide further observation of conditions of the secondary clarifier.

SAMPLING EVENT 3

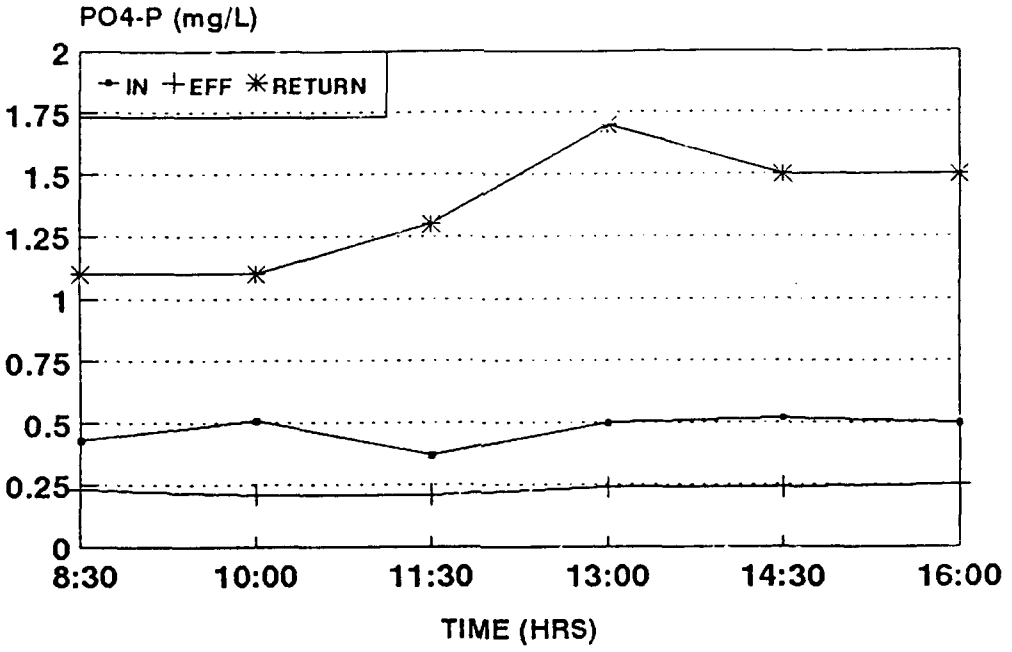
The purpose of Sampling Event 3 is to determine the mass loading of PO_4-P around the secondary clarifier. The event was conducted for an 8 hour period in accordance with the protocol summarized in Chapter 3.2.1.

Due to extremely low correlation (r^2) values for all anions on the ion chromatograph, the PO_4-P analysis was performed by the colorimetric method. The guard column in the ion chromatograph was subsequently replaced prior to future use.

Throughout the 8 hour event, PO_4-P levels of the secondary clarifier influent and effluent remained relatively constant, with a slight increase in the PO_4-P level in the return as shown in figure 4.7. Conversely, flowrates more than doubled through the event as shown in figure 4.8. The pH level of all samples remained steady between 7.0 to 7.2 throughout the event.

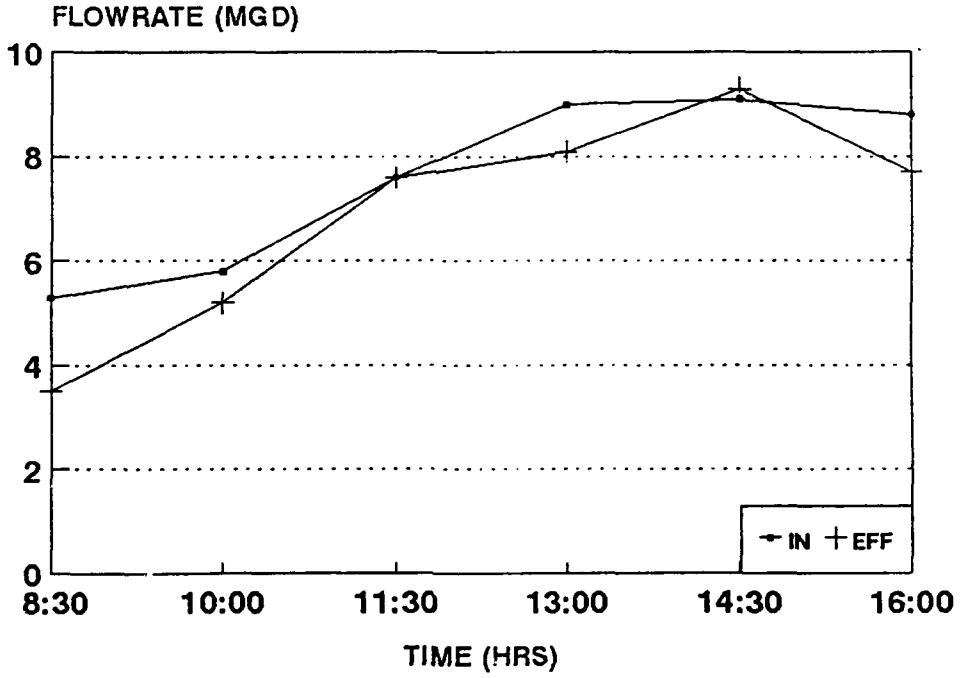
As expected, the secondary clarifier effluent PO_4-P levels ere approximately one-half the influent levels, which confirms that removal of phosphorus in the clarifier is achieved by either incorporation into complexes by aluminum or into cells by microbes and subsequent settling. Although PO_4-P levels in the recycle flow were 3 mg/L less on the average than in previous two sampling events, the values were still higher than the influent to the secondary clarifier. Therefore, it can be concluded that anaerobic activity in the clarifier blanket is releasing PO_4-P. In a follow-on pilot study, the time and rate of PO_4-P release under ideal conditions will be analyzed.

FIGURE 4.7 - SAMPLING EVENT 3
PO4-P VS TIME



SAMPLING POINTS: SECONDARY CLARIFIER INFLUENT (IN), PLANT EFFLUENT (EFF) AND RETURN SLUDGE TO ORBAL SYSTEM

FIGURE 4.8 - SAMPLING EVENT 3
FLOWRATE VS TIME



SAMPLE POINTS: EAST SIDE PLANT INFLUENT (IN) AND TOTAL PLANT EFFLUENT (EFF)

As noted in table 4.3, the return sludge rate (from the secondary clarifier to compartment A of the nitrification basin) is 4.61 MGD which is a significant percentage of the overall basin flowrate. If there are high amounts of PO_4-P in this recycle flow, the overall phosphorus loading on the basin system may likewise be significant. This effect will be discussed in Chapter 4.4.

Table 4.3 - Other Plant Data for Sampling Event 3

LOCATION	WASTE SLUDGE (GPD)	RETURN SLUDGE (MGD)
EAST	160,000	4.67
WEST	60,000	1.68

4.3 PILOT STUDIES 1-13

PILOT STUDY 1

The purpose of Pilot Study 1 is to analyze the rate of biological phosphorus release from mixed liquor drawn prior to secondary clarification. Aerobic and anaerobic environments were established in Reactor A and B, respec

Within the first 20 minutes of the study, the pH in both reactors increase by 0.7. For the remainder of the study, the pH in Reactor A remaining steady while the pH in Reactor B increased to a level of 8.4 by minute 180 and remained steady until the conclusion of the study. This rise in pH from 7.0 to 8.0 in reactor A and 7.1 to 8.4 in reactor B due to the stripping of carbon dioxide created by the addition of oxygen and nitrogen in the two reactors, respectively. The pH difference between Reactors A and B may have had a minor affect on PO_4-P release. The pH should be maintained in future pilot studies to (1) simulate typical plant levels and (2) ensure that aluminum is not returned to soluble form which may occur if the pH rises. Most importantly, this will permit a better examination of biological phosphorus release by eliminating any release due to a change in pH. Carbonate will be used to maintain the pH.

As anticipated, oxygen was maintained in Reactor A above 8 mg/L while it dropped to zero in Reactor B due to the infusion of nitrogen. Temperatures remained nearly constant throughout the experiment in both reactors as shown in table 4.4:

Table 4.4 - Temperature Readings for Pilot Study 1

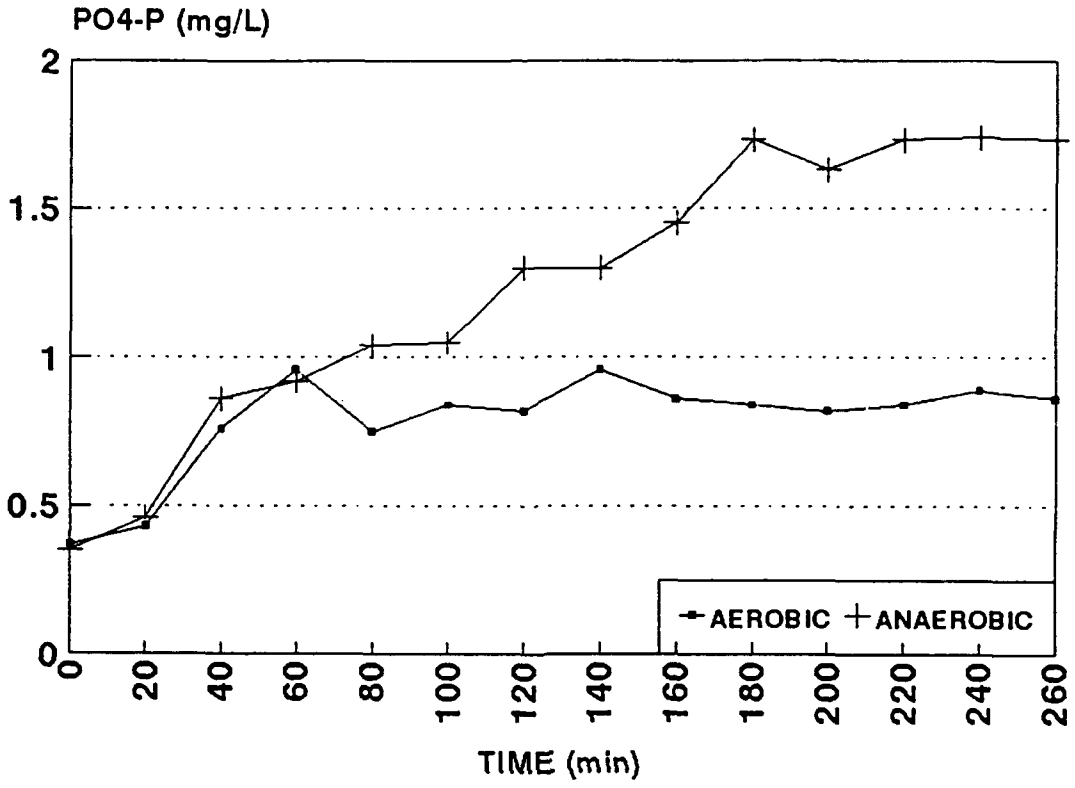
Initial = 19.5 °C

	Reactor (°C)	
Time	A	B
60	19.0	20.3
180	21.5	19.2
260	21.3	19.2

As shown in figure 4.9, the PO_4-P level in Reactor A doubled within the first 80 minutes; however, remained steady throughout the remainder of the study. In Reactor B, the PO_4-P level rose throughout the exercise, peaking at 1.74 mg/L. Although the PO_4-P levels were higher in the anaerobic reactor vice the aerobic reactor, as expected, the release of 1.74 mg/L is extremely lower than documented levels of 6 to 24 mg/L (Hong *et al.*, 1982) in similar experiments. Due to the low levels of PO_4-P release, the potential for luxury uptake of PO_4-P is questionable.

Additionally, the flowrates for nitrogen and air should be known. The reactor period should also be increased in future experiments to evaluate PO_4-P for an extended length of time.

FIGURE 4.9 - PILOT STUDY 1
PO4-P VS TIME



PILOT STUDY 2

The purpose of Pilot Study 2 was to observe the effects of a more readily degradable substrate on biological PO_4-P removal for an extended period of time while maintaining uniform gas rates and pH.

Three reactors were utilized as summarized below in table 4.5:

Table 4.5 - Reactor Conditions Pilot Study 2

REACTOR	AERATION STATE	SUBSTRATE ADDED
A	AEROBIC	0
B	ANAEROBIC	0
C	ANAEROBIC	250 mg/L

The substrate used in Reactor C was 250 mg/L of acetate as acetic acid. In order to stabilize pH, 350 mg/L of sodium bicarbonate was added to each reactor.

Within the first 20 minutes of the study, the pH in all three reactors rose approximately 0.5 units, but remained relatively stable the remainder of the study. Temperatures also remained stable between 20.4 and 22.7 °C as shown in table 4.6 below:

Table 4.6 - Temperature Readings for Pilot Study 2

Initial = 17.2 °C

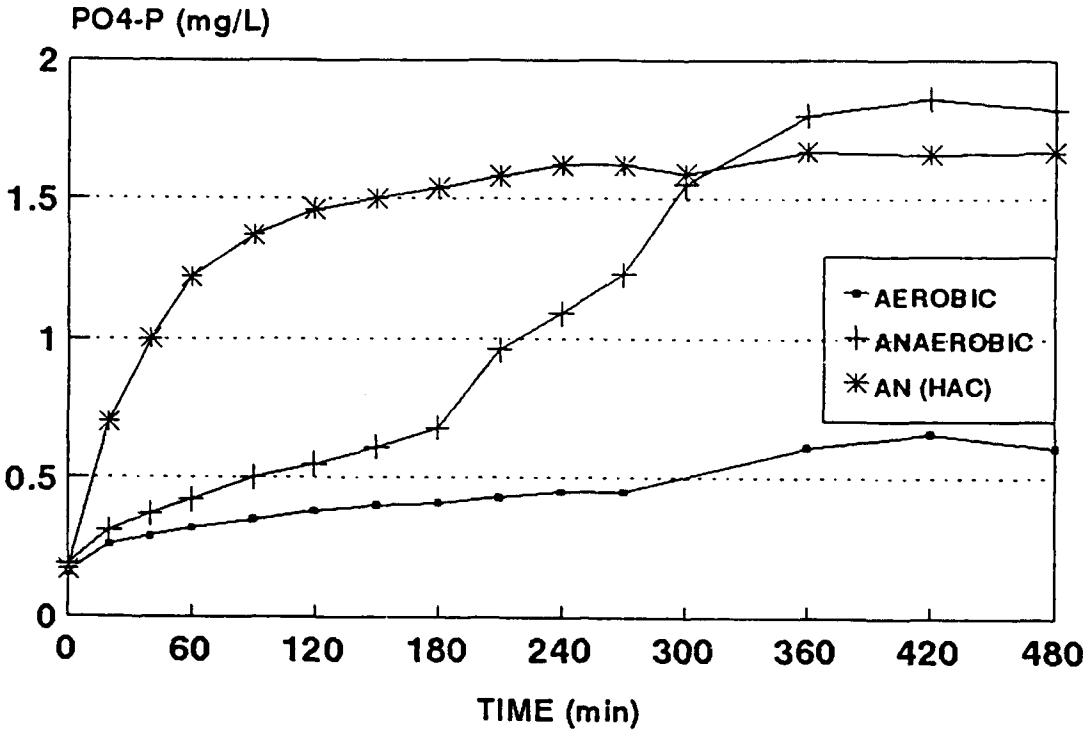
	Reactor (°C)		
Time	A	B	C
90	20.5	20.4	21.2
180	21.8	21.3	21.8
240	22.4	21.6	22.3
300	22.5	21.4	22.5
360	22.6	22.0	22.1
420	22.5	22.1	22.7
480	22.4	21.8	22.4

As shown in figure 4.10, the PO_4-P level in Reactor A

increased from 0.16 to 0.61 mg/L over the 8 hour period. In both of the anaerobic reactors, the PO_4-P release was substantially higher and peaked in the 1.7 mg/L range. In Reactor B, a significant increase in PO_4-P release occurred between the 3 hour and 6 hour marks while the PO_4-P release in Reactor C with substrate addition was nearly instantaneous, increasing nearly 900% in the first 2 hours. This rapid release of PO_4-P observed in Reactor C compared to Reactors A and B can be attributed to the substrate provided for anaerobic growth. Since soluble COD was still in supply in Reactor B and C (104 and 200 mg/L, respectively) at the conclusion of the study, the potential for further growth remained. However, since PO_4-P release did not continue for the second half of the study in Reactor C and for the final 2 hours in Reactor B, it can be concluded that growth was not sustained. The release of PO_4-P in Reactor A was substantially less than in Reactors B and C as expected when observing aerobic versus anaerobic growth. However, as observed in Pilot Study 1, the maximum amount of PO_4-P release was extremely low (less than 2 mg/L in Reactor C).

In order to increase the initial microbial seed population in future pilot studies, the wastewater will be allowed to settle and supernatant will be drawn off resulting in a more concentrated samples.

FIGURE 4.10 - PILOT STUDY 2
PO4-P VS TIME



AN (HAC) = ANAEROBIC W/ 250 mg/L ACETATE ADDED AS ACETIC ACID
350 mg/L NaHCO3 ADDED TO ALL REACTORS

PILOT STUDY 3

The purpose of Pilot Study 3 was to observe the uptake of PO_4-P when anaerobic reactors are subjected to aerobic conditions. Aerobic conditions were established in Reactor A while Reactors B and C were anaerobic. All three reactors contained a buffer to maintain pH. After 4 hours of anaerobic conditions, Reactors B and C were subjected to aerobic conditions and analyzed for an additional 1 1/2 hours. Reactor A remained aerobic throughout the pilot study. Reactor C was supplemented with 250 mg/L of substrate in the form of acetate as acetic acid. A sample was analyzed for PO_4-P by the colorimetric method to confirm accuracy of ion chromatograph results.

The initial TSS in the mixed liquor was 3950 mg/L. Within the first hour of the study, the pH in all three reactors rose to approximately 8.0 and remained steady for the study. Temperatures also remained stable rising slowly toward room temperature as shown in table 4.7 below:

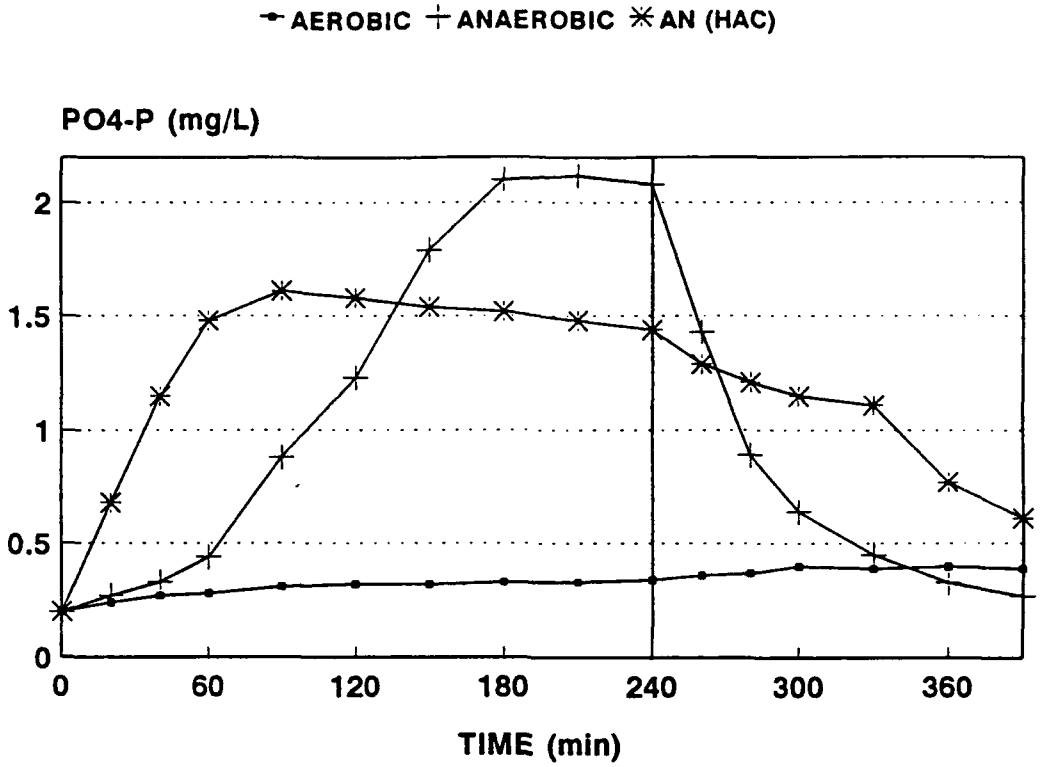
Table 4.7 - Temperature Readings for Pilot Study 3

Initial = 18.5 °C

	Reactor (°C)		
Time	A	B	C
60	19.6	19.8	19.8
120	20.8	21.4	21.3
180	21.1	22.0	21.9
260	21.5	22.6	22.4
360	21.9	22.5	22.6

The effects of the study conditions on soluble phosphorus are shown in figure 4.11. In Reactor A, which was subjected to aerobic

FIGURE 4.11 - PILOT STUDY 3
PO4-P VS TIME



AN (HAC) = ANAEROBIC W/ 250 mg/L ACETATE AS ACETIC ACID
350 mg/L NaHCO3 ADDED TO ALL REACTORS
AN (HAC) AND ANAEROBIC REACTORS SWITCHED TO AERATION AT T = 240

conditions, the PO_4-P level remained stable, increasing minimally from 0.20 to 0.39 mg/L. In Reactor C, supplemented with acetate, the increase in PO_4-P was similar to Pilot Study 1, while in Reactor B, the PO_4-P release was delayed, but rose sharply to 2.12 mg/L. At t=260 minutes, when Reactors B and C were subjected to aerobic conditions, the PO_4-P levels dropped sharply leveling within 0.3 mg/L of Reactor A as expected. Based on the results, a future experiment should be conducted using an aerobic reactor to determine levels of PO_4-P at various pH levels.

The initial soluble COD of the wastewater was 21 mg/L and the

final soluble COD remained the same in reactors B and C. However, in Reactor C, soluble COD dropped from the added COD of 250 mg/L plus the initial wastewater COD to a final soluble COD of 27 mg/L which indicates that the substrate was nearly depleted. In order to better understand the effects of soluble COD under anaerobic conditions, future studies should utilize varying quantities of substrate.

A sample from Reactor B was split and analyzed for PO_4-P by ion chromatography and colorimetrically. The difference between the two methods was only 0.02 mg/L, thereby maintaining a high level of confidence in the ion chromatograph data.

PILOT STUDY 4

The purpose of Pilot Study 4 was to observe the effects of varying quantities of acetate substrate on phosphorus release in an anaerobic environment. Substrate in the quantities of 250 and 750 mg/L acetate as acetic acid was added to Reactors B and C, respectively. No additional substrate was added to Reactor A.

The initial TSS in the mixed liquor was 3930 mg/L. Within the first hour of the study, pH levels in Reactors A and B rose and steadied at approximately 8.5, while Reactor C, with the high acetate addition, reached a pH of slightly more than 7.5. The temperatures and DO readings are shown in table 4.8 below:

Table 4.8 - Temperature and DO Readings for Pilot Study 4

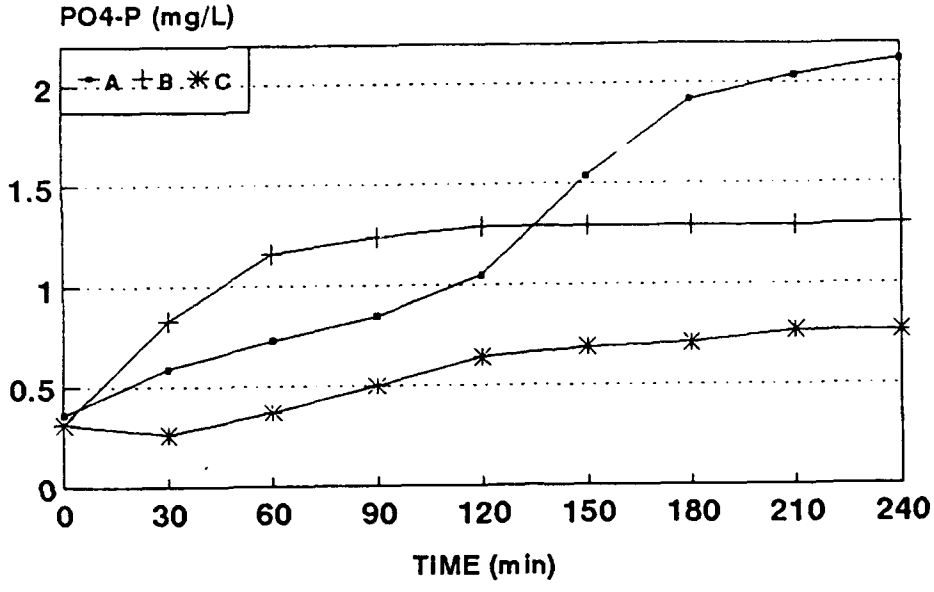
Initial Temp = 18.7 °C

PARAMETER	A	B	C
Temp (°C) at t= 240	22.0	21.9	21.9
Initial DO (mg/L)	2.9	3.4	2.6

Note: At all other times DO < 0.3 mg/L

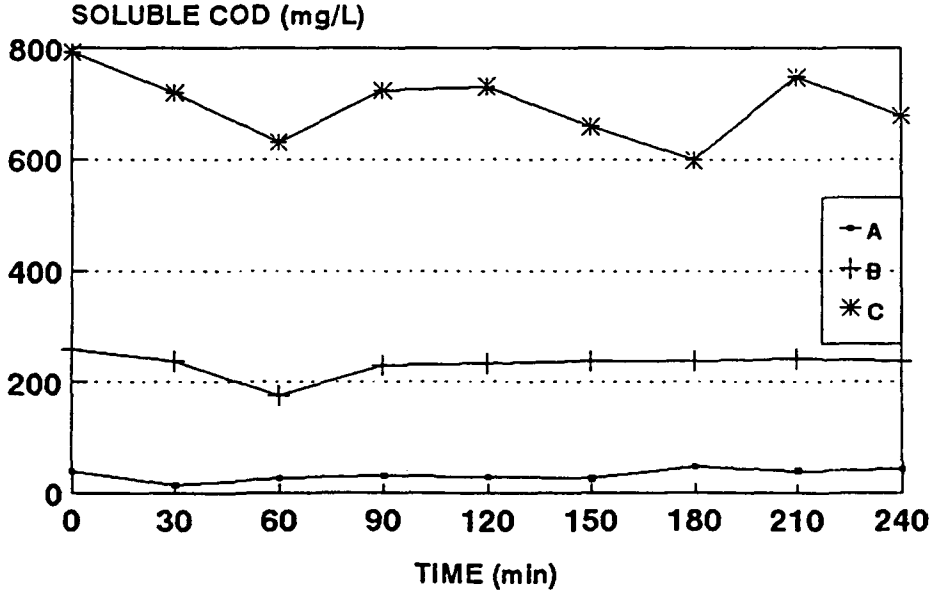
As shown in figure 4.12, PO_4-P levels in Reactors B and C rose slowly, peaking at 1.3 and 0.77 mg/L, respectively. PO_4-P levels in Reactor A also rose slowly through the first two hours, but jumped to a level of 2.12 mg/L by the completion of the study. However, as shown in figure 4.13, the soluble COD dropped only slightly throughout the experiment in all three reactors. This consistency of soluble COD in Reactors B and C over time was not expected. It was anticipated that the soluble COD would drop over

FIGURE 4.12 - PILOT STUDY 4
PO4-P VS TIME
ALL REACTORS ANAEROBIC



B: 250 mg/L ACETATE ADDED AS ACETIC ACID
C: 750 mg/L ACETATE ADDED AS ACETIC ACID
350 mg/L NaHCO3 ADDED TO ALL REACTORS

FIGURE 4.13 - PILOT STUDY 4
SOLUBLE COD VS TIME
ALL REACTORS ANAEROBIC



B: 250 mg/L ACETATE ADDED AS ACETIC ACID
C: 750 mg/L ACETATE ADDED AS ACETIC ACID
350 mg/L NaHCO3 ADDED TO ALL REACTORS

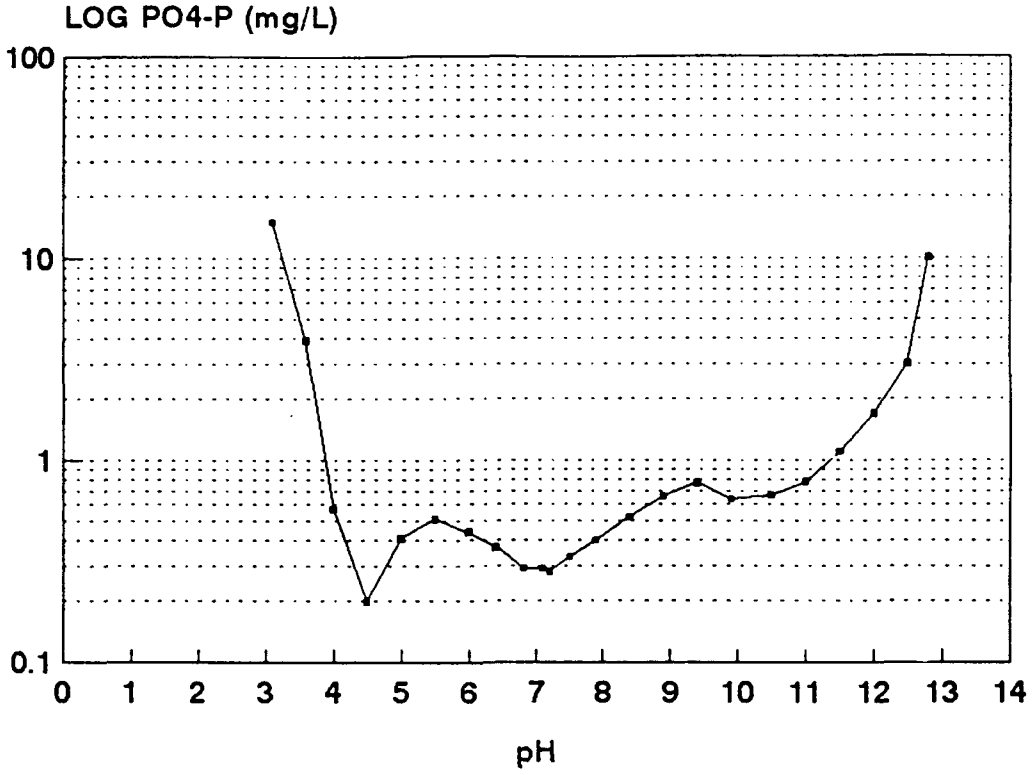
time in Reactors B and C resulting in a release of PO_4-P over time due to anaerobic microbe growth. This did not occur. Since the results are suspect, a similar pilot study will be completed.

PILOT STUDY 5

The purpose of Pilot Study 5 is to determine PO_4-P levels at various pH values by titrating an aerobic sample up in pH with a basic solution and down with an acidic solution. For the titration, the pH was decreased in Reactor A and increased in Reactor B using 2N solutions of NaOH and H_2SO_4, respectively. Samples were drawn from each reactor approximately every 0.5 unit change in pH.

The TSS of the mixed liquor used in each of the reactors was 5750 mg/L. As shown in figure 4.14, PO_4-P levels increased gradually in both reactors as the pH was adjusted and did not exceed 1 mg/L until a pH of 3.6 in Reactor A and 11.5 in Reactor B were reached. As expected, the recorded PO_4-P levels generate a coagulation diagram of typical shape, with higher levels of PO_4-P at extreme pHs and lower levels of PO_4-P at mid-range pHs. However, the extreme pHs did not generate PO_4-P levels as high as anticipated. With an average influent containing 8 mg/L of total phosphorus, a detention time of 10 days in the clarifier, negligible wastage volumes from the clarifier compared to recycle volumes and an effluent phosphorus level of only 0.5 mg/L, one would expect the total phosphorus levels within the process to reach 80 mg/L. The maximum phosphorus level recorded in Pilot Study 5 was 31 mg/L at a pH of 11. The use of the ion chromatograph at high and low pH levels may have resulted in inaccurate readings; therefore, the experiment should be repeated by testing for phosphorus colorimetrically.

FIGURE 4.14 - PILOT STUDY 5
LOG PO4-P VS pH



PILOT STUDY 6

The purpose of Pilot Study 6 is to observe the effects of varying quantities of substrate addition on PO_4-P release under anaerobic conditions. Reactors B, C and D received substrate in the amounts of 100, 200 and 300 mg/L acetate as acetic acid, respectively. No additional substrate was added to Reactor A.

The initial TSS in the mixed liquor were 7750 and 5920 mg/L for Reactors A/B and C/D, respectively. Within the first two hours of the study, pH levels in all four reactors had increased to a level of just above 8 and remained steady for the remainder of the study. As below shown in table 4.9, temperature increased during the experiment and DO readings were negligible after the start of the study:

Table 4.9 - Temperature and DO Readings for Pilot Study 6

Initial Temp = 17.4 °C

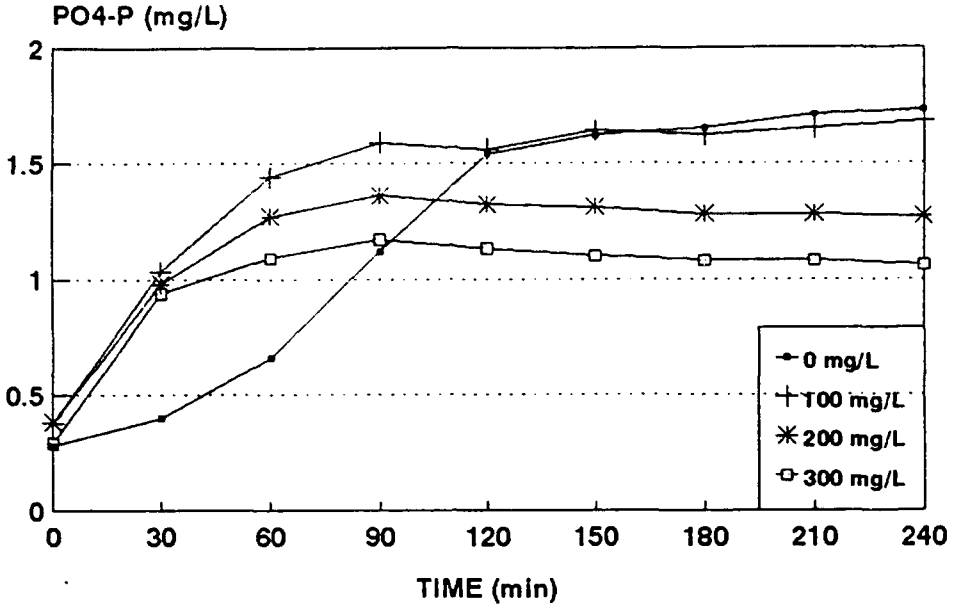
Parameter	A	B	C	D
Temp (°C) at t=240	23.3	23.4	23.5	23.4
Initial DO (mg/L)	5.8	5.8	4.7	4.7

Note: DO < 0.3 mg/L at all other times

In reactors with substrate addition, the PO_4-P levels rose sharply in the first hour, but leveled between 1 and 1.5 mg/L as noted in figure 4.15. The PO_4-P release lagged in Reactor A (no substrate addition), but also reached a level of 1.5 mg/L.

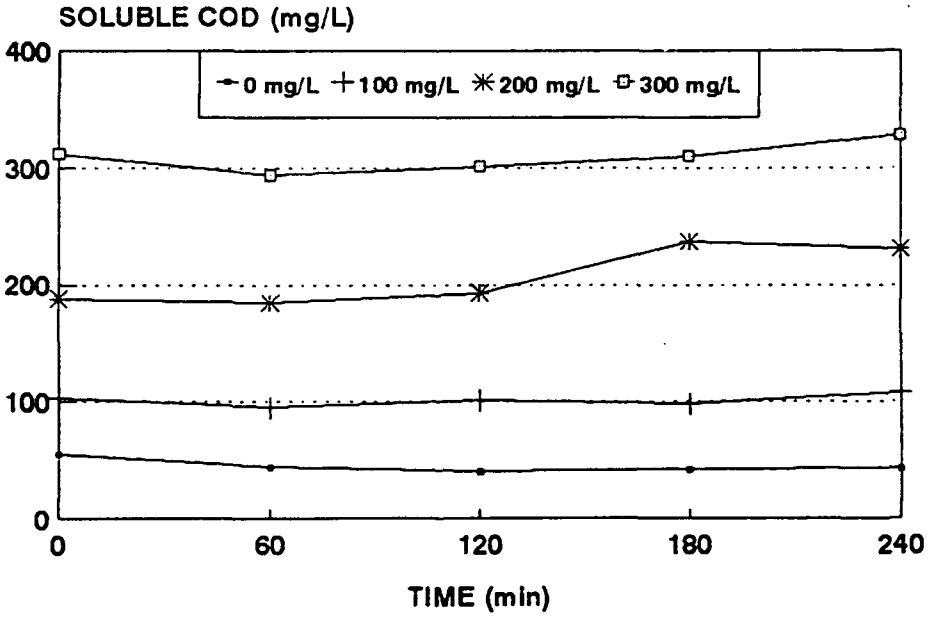
Similar to Pilot Study 4, soluble COD levels remained relatively constant in all four reactors as shown in figure 4.16. Due to this lack of soluble COD reduction, in addition to the low

FIGURE 4.15 - PILOT STUDY 6
PO4-P VS TIME
ALL REACTORS ANAEROBIC



LEGEND AMOUNTS = ACETATE ADDED AS ACETIC ACID
350 mg/L NaHCO3 ADDED TO ALL REACTORS

FIGURE 4.16 - PILOT STUDY 6
SOLUBLE COD VS TIME
ALL REACTORS ANAEROBIC



LEGEND AMOUNTS = ACETATE ADDED AS ACETIC ACID
350 mg/L NaHCO3 ADDED TO ALL REACTORS

level of PO_4-P release, it can be concluded that microbial growth was minimal at best. In other words, it can be concluded that the microorganisms are not generating ATP and subsequently, are not releasing PO_4-P. In fact, the PO_4-P release is inversely proportional to the quantity of substrate added in Reactors B, C and D. A preliminary conclusion is that the microorganisms at the Yellow River Sweetwater Creek Plant are incapable of adequately removing PO_4-P at an enhanced rate.

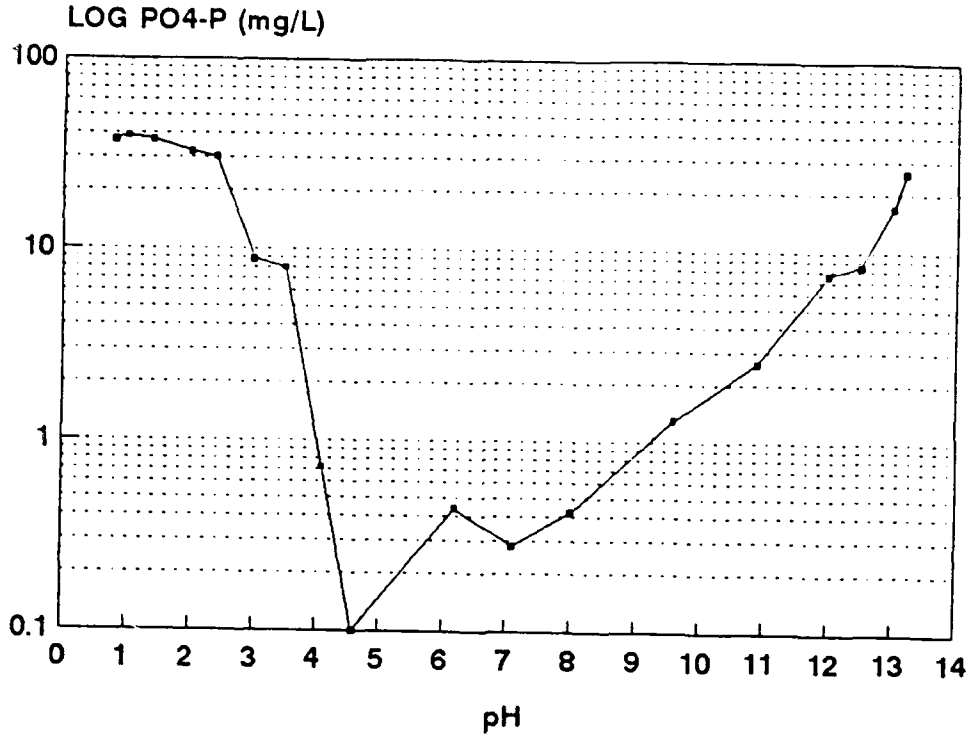
PILOT STUDY 7

The purpose of Pilot Study 7 is to determine PO_4-P levels of a secondary clarifier mixed liquor sample at various pHs by titrating up in pH with a basic solution and down in pH with an acidic solution. Differing from Pilot Study 5, samples were analyzed for PO_4-P colorimetrically to avoid analysis interference at extreme pH values. For the titration, the pH was decreased in Reactor A and increased in Reactor B using 2N solutions of NaOH and H_2SO_4, respectively. In Reactor B at pH values greater than 11, 5N NaOH was used to raise pH. In Reactor A at pH values less than 2.5, 11N H_2SO_4 was used to lower pH and at pH values less than 1.5, 32N H_2SO_4 was used to lower pH. Samples and readings were taken every one pH unit between 5 and 9 and every 0.5 pH unit less than 5 and greater than 9.

The TSS of the mixed liquor used in each of the reactors was 8500 mg/L. The total phosphorus of the mixed liquor was 210 mg/L or 2.5% of the TSS. As shown in figure 4.17, PO_4-P levels increased gradually in both reactors and did not exceed 1 mg/L in Reactor A until a pH of 3.5 was achieved and in Reactor B until reaching a pH of 9.6. The results were similar to Pilot Study 5 in which the ion chromatograph was used to quantify PO_4-P. Excessive quantities of NaOH were necessary to raise the pH above 13.2; therefore, no samples were analyzed for PO_4-P above this pH.

It can be concluded that the maximum amount of PO_4-P in this mixed liquor sample is just under 40 mg/L, since the soluble phosphorus values remained steady in Reactor A below pH values of

FIGURE 4.17 - PILOT STUDY 7
LOG PO4-P VS pH



2. From the above determination, the amount of phosphorus bound in microbial cells can be approximated by subtracting the maximum soluble phosphorus (35 mg/L) from the total phosphorus (210 mg/L), yielding 175 mg/L of phosphorus in the cells as shown below in figure 4.18:

Figure 4.18 - Phosphorus Summation in Pilot Study 7

Derivation of Phosphorus (P)	P (mg/L)
Initial Total P	210
$AlPO_4 = Al^{3+} + PO_4^{3-}$	-35
$C_5H_7O_2N = C_{50}H_{20}O_{20}N_{10}P = PO_4^{3-}$	175 in cells

Therefore, the mixed liquor has a cellular phosphorus content of 2.1% which is calculated by dividing the total phosphorus by the cell mass by the TSS and multiplying by 100%.

PILOT STUDY 8

The purpose of Pilot Study 8 is to determine the phosphorus uptake rate under ideal conditions in an aerobic environment. Additives to Reactors A and B are detailed below in table 4.10:

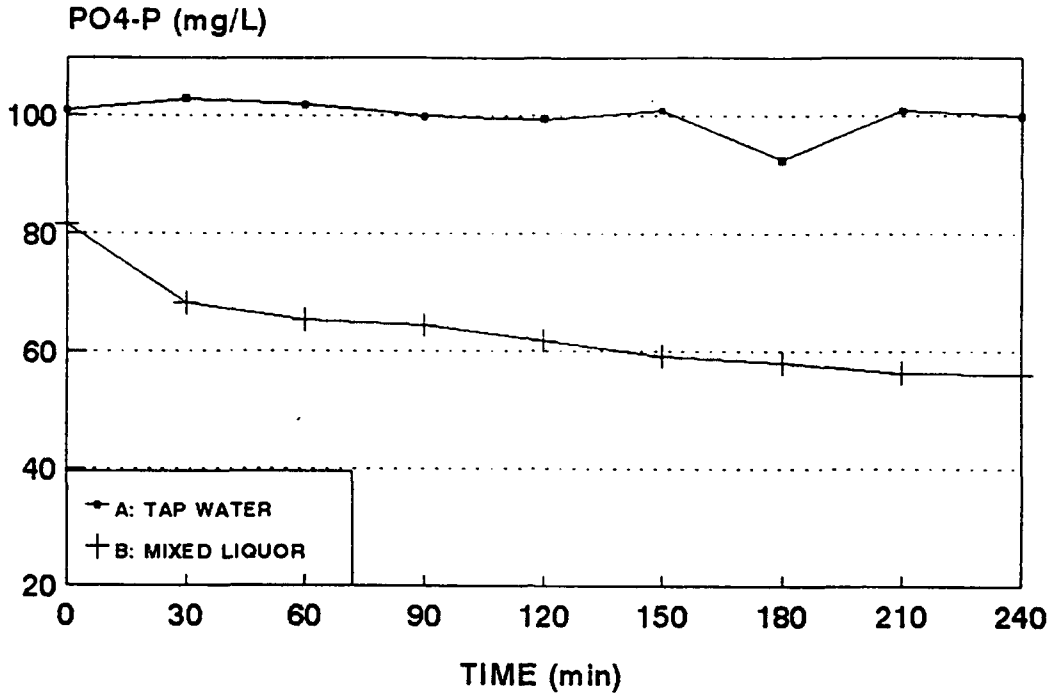
Table 4.10 - Additives to Reactors A and B in Pilot Study 8

COMPOUND	QUANTITY ADDED REACTOR A	REACTOR B
Acetic acid	0	250 mg/L
Dextrose	0	125 mg/L
Glucosamine	0	125 mg/L
Phenol	0	25 mg/L
Total COD	0	450 mg/L
Ammonium chloride	40 mg/L N	32 mg/L N
Potassium phosphate	100 mg/L P	100 mg/L P
Sodium bicarbonate	350 mg/L	350 mg/L

The pH of each reactor was maintained between 7.1 and 7.3 with solutions of 2N NaOH and H_2SO_4. An additional 8 mg/L N is provided by the glucosamine resulting in a total amount of 40 mg/L N in Reactor B.

The initial TSS of the mixed liquor was 7250 mg/L. As shown in figure 4.19, the PO_4-P level in Reactor A remained constant throughout the study, while in Reactor B, the PO_4-P level dropped sharply from 81 to 68 mg/L for the first 30 minutes and continued to decrease slowly to 56 mg/L by the end of the study. Since the change in PO_4-P over time is essentially zero in Reactor A, it can be assumed that no additional metal-phosphate complexes are being formed. In Reactor B, the soluble phosphorus level of 81.5 mg/L at t=0 is suspect, since it is considerably less the 100 mg/L added

FIGURE 4.19 - PILOT STUDY 8
PO4-P VS TIME
REACTORS AEROBIC

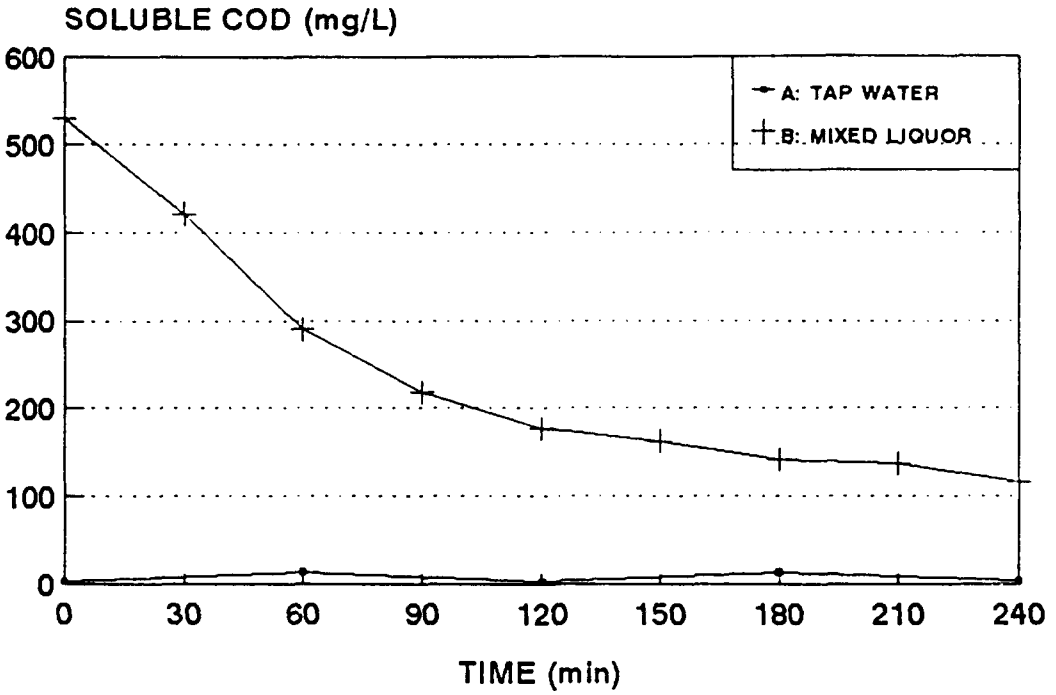


A: PO4-P + NH4-N
B: PO4-P + NH4-N + GLUCOSE + ACETIC ACID + PHENOL + GLUCOSAMINE

initially. For future experiments, steps must be taken to ensure the soluble phosphorus levels in all reactors at t=0 is equivalent.

As expected, a concurrent drop in soluble COD was also observed in Reactor B from 526 to 127 mg/L through the study, while Reactor A remained negligible, as shown in figure 4.20. Although a decrease in both soluble COD and PO_4-P was observed in Reactor B for the first 90 minutes of the study, the drop in soluble substrate (ΔS_s = 312 mg/L) is sharp compared to a steady, but gradual decrease in soluble phosphate (ΔPO_4-P = 7.1 mg/L).

FIGURE 4.20 - PILOT STUDY 8
SOLUBLE COD VS TIME
REACTORS AEROBIC



A: PO4-P + NH4-N
B: PO4-P + NH4-N + GLUCOSE + ACETIC ACID + PHENOL + GLUCOSAMINE

PILOT STUDY 9

The purpose of Pilot Study 9 is to observe the rate of PO_4-P uptake in aerobic reactors with and without substrate addition, while ensuring PO_4-P are equal in both reactors at t=0.

The first part of the pilot study was to titrate a phosphorus-enhanced solution to extreme pHs and observe phosphorus recovery. One liter of prepared mixed liquor was added to a reactor along with three liters of tap water, 40 mg/L of N as ammonium chloride and 50 mg/L of P as potassium phosphate. The potassium phosphate solution was added incrementally with 30 minutes of aeration between additions. Following the first addition of 10 mg/L, a sample was taken and after 30 minutes another sample was taken. Thereafter, 5 mg/L of potassium phosphate solution was added until a total of 50 mg/L was reached. Samples were taken after each 30 minute aeration period. All samples were analyzed for PO_4-P to observe recovery.

The second part of the pilot study was to observe the uptake of PO_4-P in the above solution. The 4 liter solution was split into two reactors ("A" and "B") with the following additions:

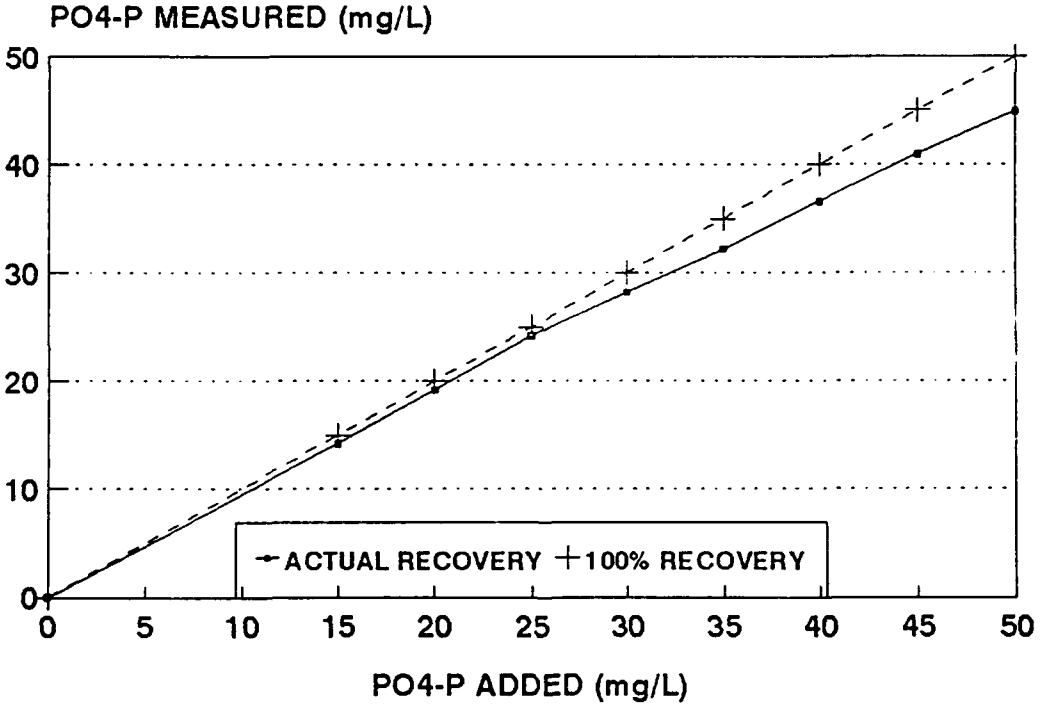
Table 4.11 - Additives to Reactors A and B in Pilot Study 9

COMPOUND	REACTOR A	REACTOR B
Acetic acid	0	250 mg/L
Dextrose	0	62.5 mg/L
Glucosamine	0	62.5 mg/L
Phenol	0	25 mg/L
Total COD Added	0	400 mg/L

Samples for analysis and readings were taken every 30 minutes.

The TSS of the prepared mixed liquor prior to the start of Part 1 was 10,760 mg/L. Immediately following the addition of 10 mg/L of PO_4-P (t=0), the solution was analyzed and contained 9.85 mg/L PO_4-P. After the 30 minutes of aeration (t=30), analysis indicated that 8.56 mg/L of PO_4-P was present. Following incremental addition of 5 mg/L PO_4-P and 30 minutes of aeration, the results shown in figure 4.21. Of note is that recovery levels were 94% or higher through the addition of 30 mg/L of PO_4-P, dropping to 90% recovery only after the addition of 50 mg/L of PO_4-P. The results for cumulative PO_4-P recovery at levels less

FIGURE 4.21 - PILOT STUDY 9
PO4-P ADDED VS MEASURED



ADDITION OF PO4-P TO MIXED LIQUOR SAMPLE AFTER ADDITION OF 10 mg/L PO4-P AND AERATION FOR 0.5 HR.

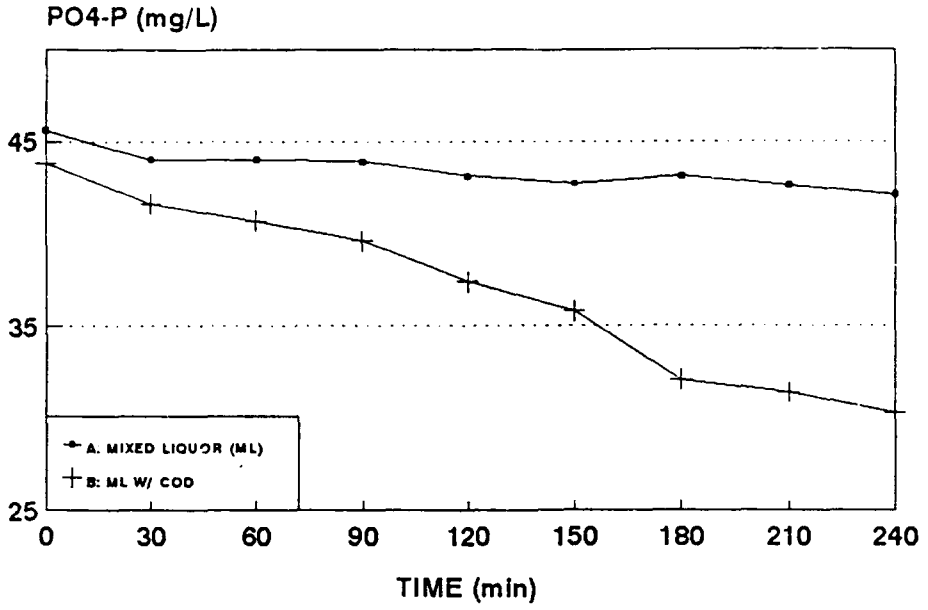
than 30 mg/L compares favorably to ion chromatograph data recovery levels of 94.1% and 97.3% for surface water and wastewater analysis, respectively, (EPA 600/4-84-017, 1984).

In second part of the pilot study, the initial PO_4-P levels were approximately equal as desired. Over time, the PO_4-P level in Reactor A dropped only slightly, while in Reactor B, PO_4-P levels decreased steadily from 43.8 to 30.3 mg/L. Concurrently, soluble COD dropped steadily in Reactor B from 335 to 65 mg/L while soluble COD in Reactor A remained steady. PO_4-P and soluble COD values are shown in figures 4.22 and 4.33, respectively.

The pH in Reactor A dropped from 6.8 to 6.4 over time; conversely, the pH rose in Reactor B from 5.5 to 7.4 over the duration of the study.

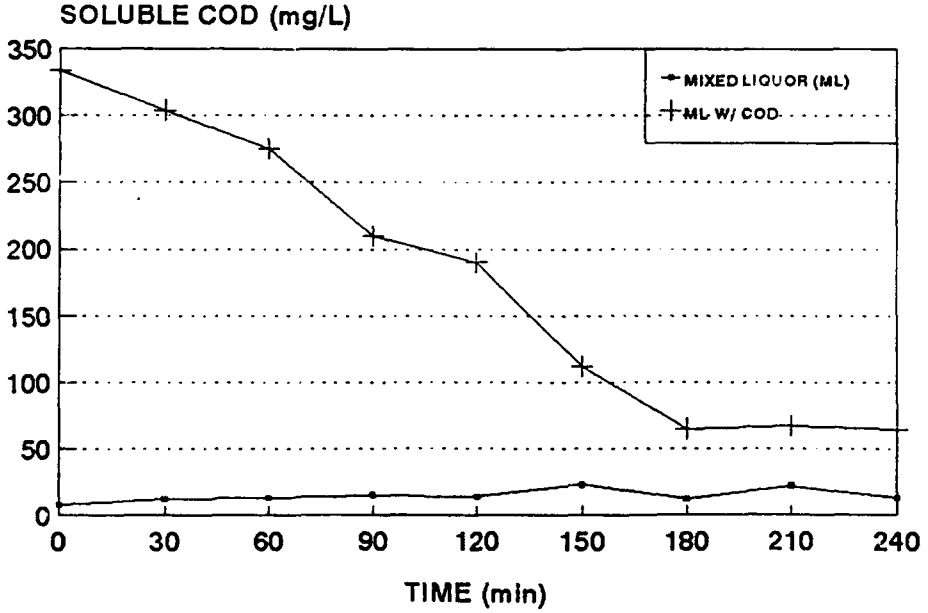
In reactor B which contained the added substrate, the ratio of soluble COD and phosphorus ($\Delta S_s/\Delta PO_4$-P) was approximately 20. This ratio compares favorable to the $\Delta S_s/\Delta PO_4$-P of 16 from Pilot Study 8. The addition of substrate in Pilot Studies 8 and 9 were 450 and 400 mg/L, respectively. Evaluation of $\Delta S_s/\Delta PO_4$-P with varying amounts of substrate should be evaluated.

FIGURE 4.22 - PILOT STUDY 9
PO4-P VS TIME
REACTORS AEROBIC



ML: PO4-P + NH4-N
ML W/ COD: PO4-P + NH4-N + DEXTROSE + ACETIC ACID + PHENOL + GLUCOSAMINE

FIGURE 4.23 - PILOT STUDY 9
SOLUBLE COD VS TIME
REACTORS AEROBIC



ML: PO4-P + NH4-N
ML W/ COD: PO4-P + NH4-N + DEXTROSE + ACETIC ACID + PHENOL + GLUCOSAMINE

PILOT STUDY 10

The purpose of Pilot Study 10 is to observe the rate of PO_4-P uptake in aerobic reactors over a wide range of substrate values. Ammonium chloride and potassium phosphate were added to 8 liters of prepared mixed liquor in the amounts of 40 mg/L of N and 50 mg/L of P, respectively. Two liters of the above solution was distributed to four reactors and the compounds listed below in table 4.12 were added:

Table 4.12 - Additives to Reactors A-D in Pilot Study 10

	QUANTITY ADDED			
COMPOUND	REACTOR A	REACTOR B	REACTOR C	REACTOR D
Sodium bicarbonate (mg/L)	350	350	350	350
Acetic acid (mg/L)	0	30	150	300
Dextrose (mg/L)	0	18.75	37.5	75
Glucosamine (mg/L)	0	18.75	37.5	75
Phenol (mg/L)	0	7.5	15	30
TOTAL COD ADDED (mg/L)	0	120	240	480

The TSS of the prepared mixed liquor was 11,030 mg/L. The PO_4-P levels dropped slowly in all four reactors over time as shown in figure 4.24, with the largest change occurring in Reactor D, where the concentration of PO_4-P decreased from 53.2 to 47.4 mg/L. Soluble COD decreased in Reactors A, B and C with the final levels measured below 100 mg/L as shown in figure 4.25. The pH level in Reactors A, B, and C were similar rising slightly through the experiment to a level just above 8.

FIGURE 4.24 - PILOT STUDY 10
PO4-P VS TIME
REACTORS AEROBIC

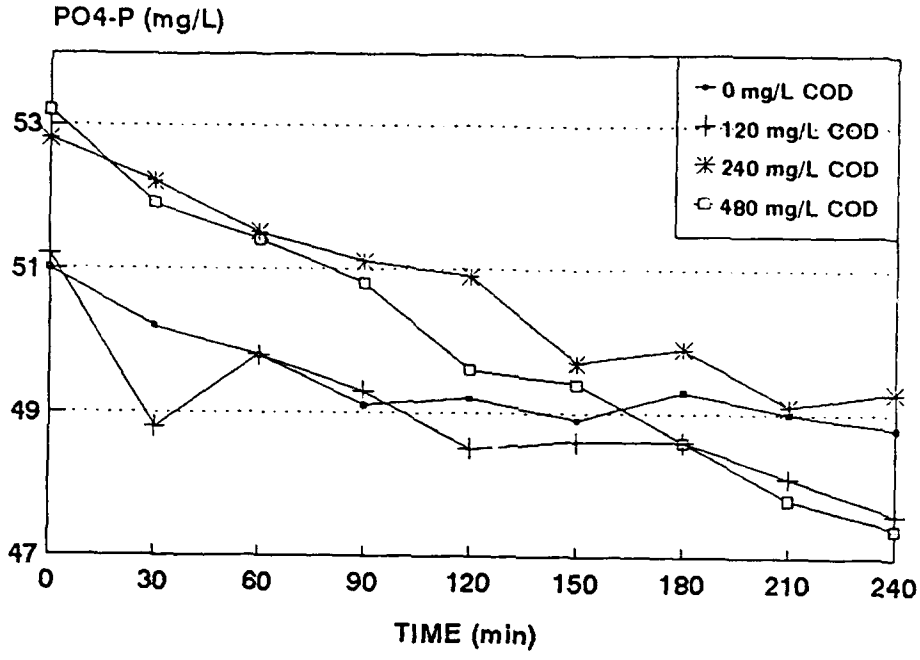
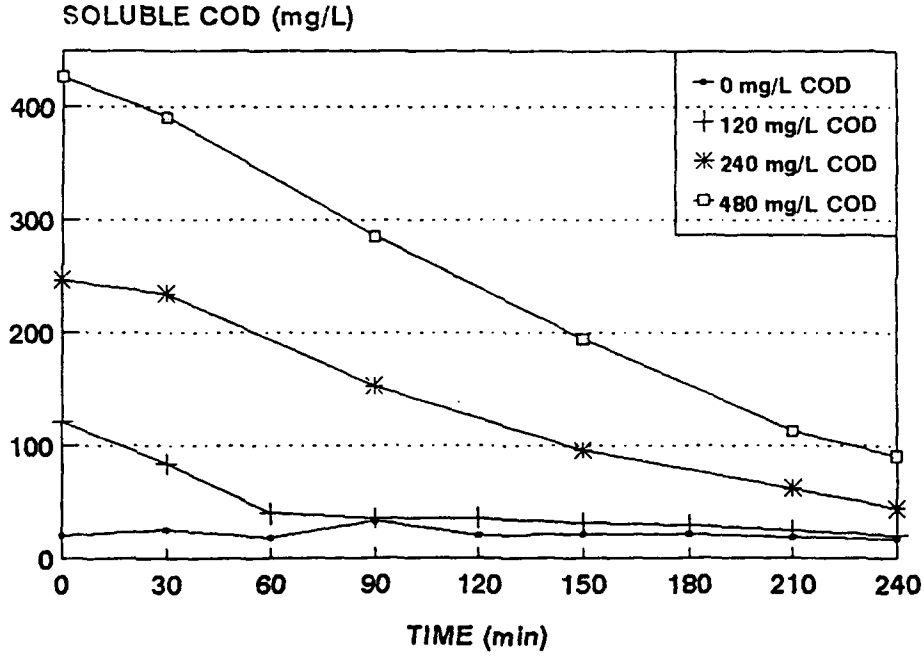


FIGURE 4.25 - PILOT STUDY 10
SOLUBLE COD VS TIME
REACTORS AEROBIC



Listed below in table 4.13 is a summary showing the soluble substrate added, the PO_4-P uptake and pH change for reactors in Pilot Study 9 and 10:

Table 4.13 - Comparison of ΔpH and ΔPO_4-P in Pilot Studies 9 and 10

PILOT STUDY	S_s ADDED (mg/L)	DIFFERENCE (INITIAL-FINAL)	
		pH	PO_4-P (mg/L)
9	0	-0.4	3.5
10	**0**	**+0.2**	**2.2**
9	400	+1.9	13.5
10	**480**	**+1.8**	**5.8**
10	**240**	**+1.1**	**3.5**
10	**120**	**+1.4**	**2.2**

As shown above, the PO_4-P uptake rates in Pilot Studies 9 and 10 are not similar. Of note, is that all final pH readings in Pilot Study 9 are greater than 8 which may have negatively affected PO_4-P uptake.

PILOT STUDY 11

The purpose of Pilot Study 11 is to observe the PO_4-P uptake rate of plant raw waste, seeded with mixed liquor under aerobic conditions. Ammonium chloride and potassium phosphate in the amounts of 40 mg/L of N and 50 mg/L of P, respectively were added to the prepared mixed liquor and the solution was aerated for 30 minutes. Samples were taken and analyzed for total P and PO_4-P and 500 mL of the mixture was placed in reactors A and B. 1500 mL of raw waste drawn from the head of the plant was added to Reactor A and 1500 ml of tap water was added to Reactor B.

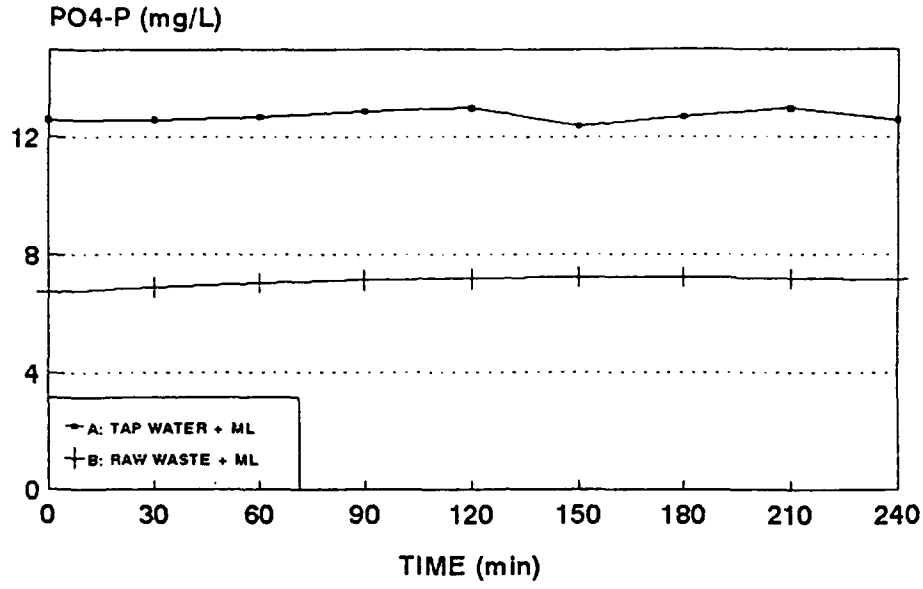
Results for total phosphorus, PO_4-P and soluble COD prior to distribution to the reactors are shown below:

Table 4.14 - PO_4-P and S_s Prior to Reactor Start in Pilot Study 11

SAMPLE	TOTAL P (mg/L)	PO_4-P (mg/L)	S_s (mg/L)
Mixed Liquor (Initial)	-	0	-
Mixed Liquor (After aeration)	95	46.4	-
Raw waste	9.8	1.73	197
Reactor A (at t=0)	22.5	6.72	110

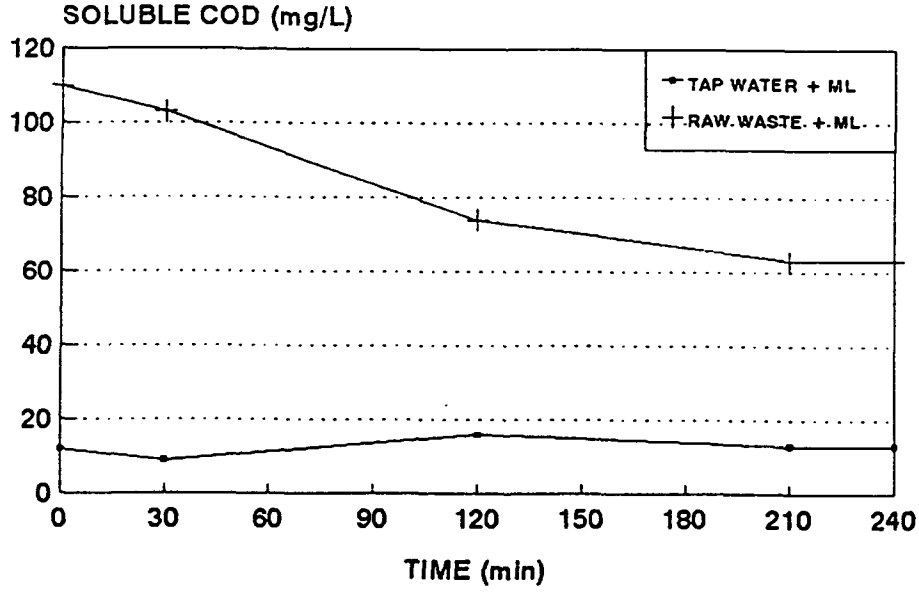
Throughout the two hour study, PO_4-P levels remained constant in both reactors as shown in figure 4.26. The soluble COD in Reactor A remained negligible throughout the study, while in Reactor B the soluble COD decreased steadily from 110 to 63 mg/L. Soluble COD results are plotted in figure 4.27. The pH in Reactor A was high

FIGURE 4.26 - PILOT STUDY 11
PO4-P VS TIME
REACTORS AEROBIC



A: TAP WATER (3/4) + ML (MIXED LIQUOR) (1/4)
B: RAW WASTE (3/4) + ML (MIXED LIQUOR) (1/4)
ML W/ 46.4 mg/L PO4-P

FIGURE 4.27 - PILOT STUDY 11
SOLUBLE COD VS TIME
REACTORS AEROBIC



A: TAP WATER (3/4) + ML (MIXED LIQUOR) (1/4)
B: RAW WASTE (3/4) + ML (MIXED LIQUOR) (1/4)
MIXED LIQUOR W/ 46.4 mg/L PO4-P ADDED

at t=0 (in excess of 9) and dropped to 8.2 after 2 hours. In Reactor B, the pH remained steady near 7 throughout the study.

By testing raw waste and mixed liquor, existing plant conditions would be simulated as close as possible. It was anticipated that within Reactor A where mixed liquor and raw waste were aerated with a spike of phosphorus, PO_4-P uptake would concurrently with the reduction in S_s. However, an uptake an PO_4-P was not detected. A pH in excess of 8 may have adversely affected microbial growth and phosphorus uptake. It is more likely however, that the microbes at the Yellow River Sweetwater Creek are incapable of luxury phosphorus uptake.

PILOT STUDY 12

The purpose of Pilot Study 12 is to observe the effects of pH on PO_4-P uptake rate of mixed liquor with substrate under aerobic conditions. A reactor containing 1.5 liters of prepared mixed liquor, 4.5 liters of tap water, 40 mg/L of N as ammonium chloride and 50 mg/L of P as potassium phosphate was aerated for 30 minutes and analyzed for PO_4-P. Two liters of the solution was added to three reactors, "A", "B" and "C", respectively, and the following compounds were added:

Table 4.15 - Additives to Reactors A-C in Pilot Study 12

	QUANTITY ADDED (mg/L)		
COMPOUND	REACTOR A	REACTOR B	REACTOR C
Sodium bicarbonate	0	350	0
Acetic Acid	0	250	250
Dextrose	0	62.5	62.5
Glucosamine	0	62.5	62.5
Phenol	0	25	25
Total COD Added	0	400	400

The prepared mixed liquor contained TSS in the concentration of 11,460 mg/L and 0 mg/L of PO_4-P. After the addition of tap water, potassium phosphate, ammonium chloride and 30 minutes of aeration, the PO_4-P level was 46.2 mg/L. The pH in both Reactors B and C rose from an initial level of 7 to slightly over 8 by the completion of the experiment. The rate of PO_4-P decrease in all three reactors was similar as shown in figure 4.28. Reactors B and C both experienced a steady drop in soluble COD from less than 400 to approximately 80 mg/L as shown in figure 4.29.

FIGURE 4.28 - PILOT STUDY 12
PO4-P VS TIME
REACTORS AEROBIC

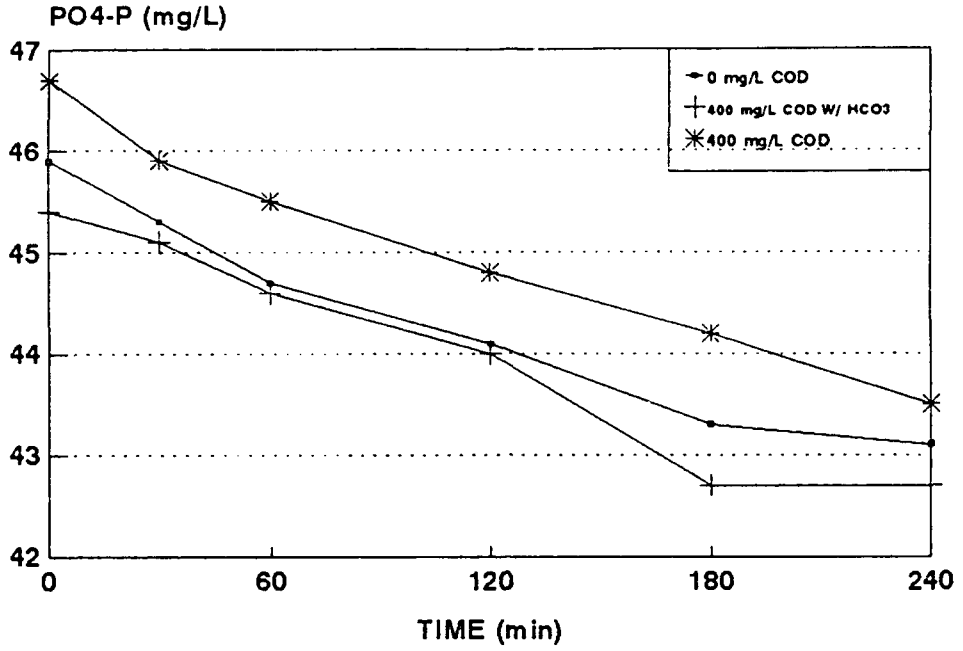
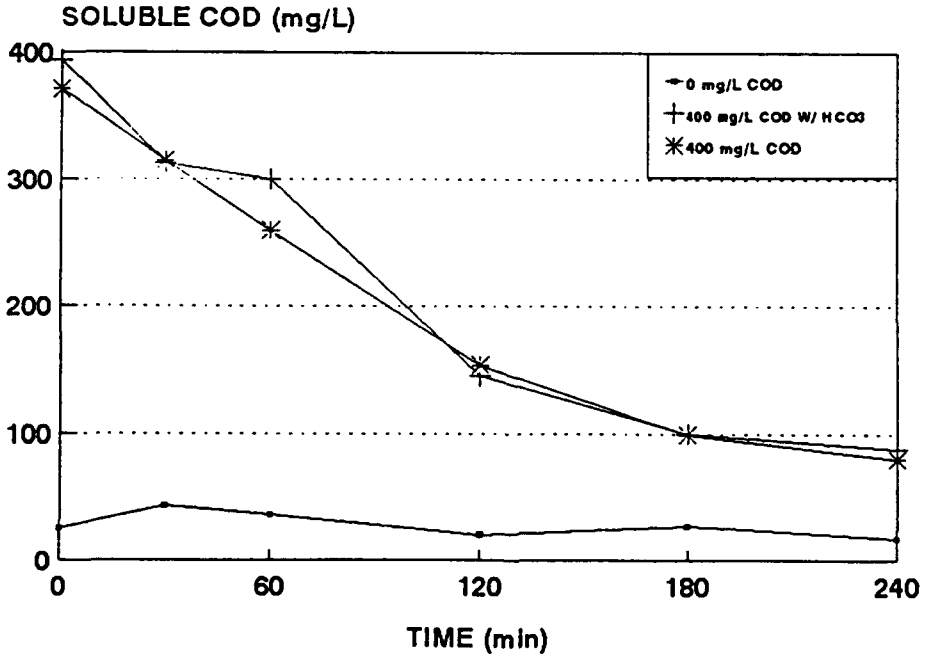


FIGURE 4.29 - PILOT STUDY 12
SOLUBLE COD VS TIME
REACTORS AEROBIC



Although PO_4-P levels dropped proportionally to S_s ($\Delta S_s/\Delta PO_4$-P) in Reactors B and C, the PO_4-P release was surprisingly low; dropping only 2.5 and 3.2 mg/L, respectively. The result was a high $\Delta S_s/\Delta PO_4$-P ratio in both Reactors B and C (approximately 112 and 91, respectively) which does not compare favorably to $\Delta S_s/\Delta PO_4$-P ratios of 16 in Pilot Study 8 and 20 in Pilot Study 9. The similarity of pH levels in Reactors B and C was unexpected, since Reactor B did not contain sodium bicarbonate to maintain pH. The pH levels were very similar to Reactor D in Pilot Study 10 where 480 mg/L of substrate and buffer were added prior to aeration. Due to the conflicting results, conditions of this pilot study will be repeated.

PILOT STUDY 13

The purpose of Pilot Study 13 is to observe the effects of pH on PO_4-P uptake rate of mixed liquor with substrate under aerobic conditions and is a repeat of Pilot Study 12. A reactor containing 1.5 liters of prepared mixed liquor, 4.5 liters of tap water, 40 mg/L of N as ammonium chloride and 50 mg/L of P as potassium phosphate was aerated for 30 minutes and analyzed for PO_4-P. Two liters of the solution was added to three reactors, "A", "B" and "C", respectively and the following compounds were added:

Table 4.16 - Additives to Reactors A-C in Pilot Study 13

	QUANTITY ADDED (mg/L)		
COMPOUND	REACTOR A	REACTOR B	REACTOR C
Sodium bicarbonate	0	350	0
Acetic Acid	0	250	250
Dextrose	0	62.5	62.5
Glucosamine	0	62.5	62.5
Phenol	0	25	25
Total COD Added	0	400	400

The prepared mixed liquor had TSS in the concentration of 10,770 mg/L and 0 mg/L of PO_4-P. After the addition of tap water, potassium phosphate, ammonium chloride and 30 minutes of aeration, the PO_4-P level was 46.7 mg/L. The pH in both Reactors B and C rose from an initial level of 7 to slightly over 8 by the completion of the experiment. As shown in figure 4.30, the steady drop in soluble COD from less than 400 to approximately 80 mg/L and minimal decrease in PO_4-P were also similar in Reactors B and C. A similar decrease in PO_4-P was likewise observed in Reactor A, as

FIGURE 4.30 - PILOT STUDY 13
PO4-P VS TIME
REACTORS AEROBIC

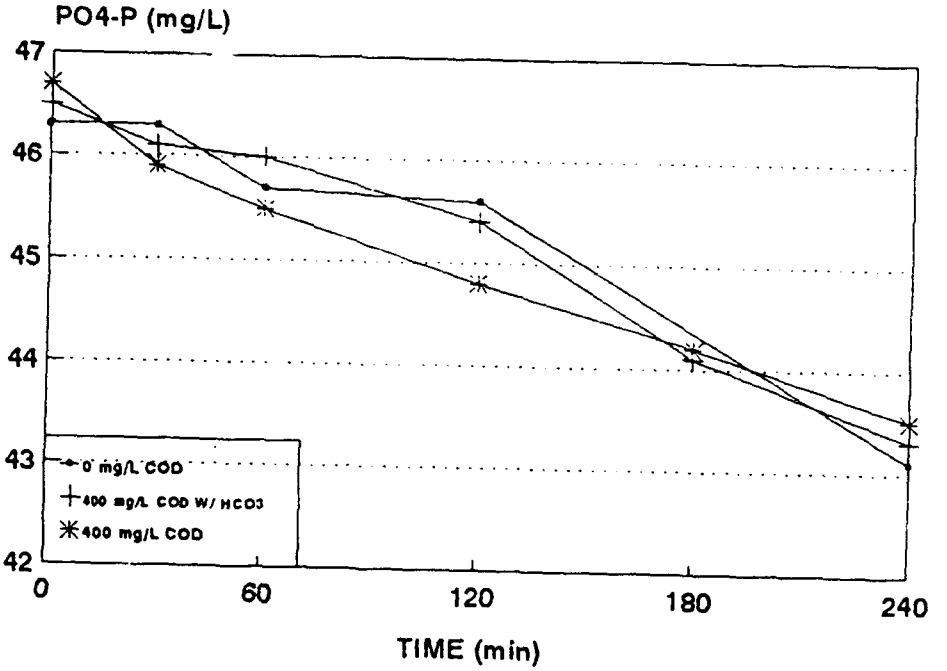
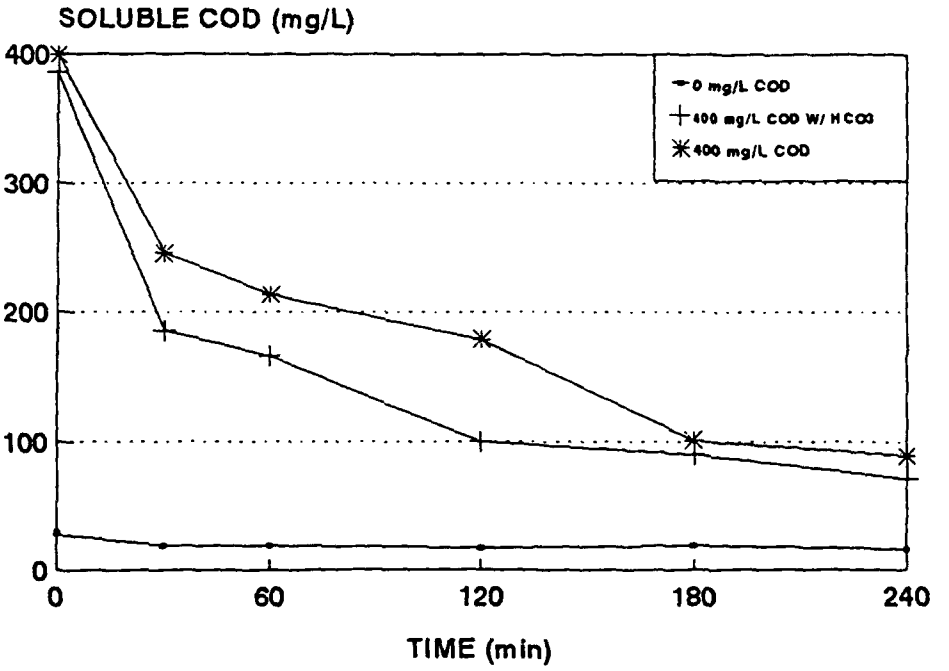


FIGURE 4.31 - PILOT STUDY 13
SOLUBLE COD VS TIME
REACTORS AEROBIC



shown in figure 4.31.

The results of this experiment were extremely similar to Pilot Study 12. Among the similarities in Reactors B and C of the two studies were (1) pH levels, (2) PO_4-P levels dropped proportionally to S_s ($\Delta S_s/\Delta PO_4$-P), (3) the $\Delta S_s/\Delta PO_4$-P ratios were high. This further confirmed that a luxury uptake of phosphorus is not occurring.

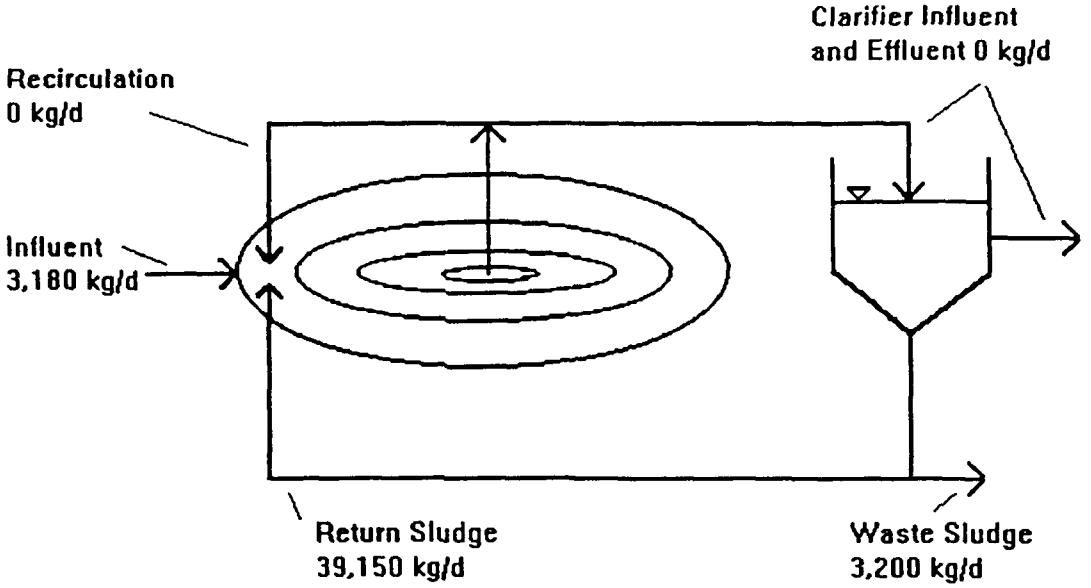
4.4 SAMPLING EVENT AND PILOT STUDY DISCUSSION

The levels of PO_4-P observed in return flows from the secondary clarifier to compartment A of the nitrification basin in the first two sampling events averaged 6.64 and 4.46 mg/L, respectively. These high levels of soluble phosphorus coupled with the return flowrates from the clarifier underflow to the basin, which are in excess of 4 MGD, have an impact on mass loading of soluble phosphorus in compartment A of the orbal system. Subsequently, mass loading around the secondary clarifier was observed in Sampling Event 3.

Since PO_4-P values for Sampling Event 2 best represent the results of the three sampling events, these values are used to analyze soluble phosphorus mass loading. By using average flowrates and PO_4-P values, soluble phosphorus mass loading was calculated at various locations. These values are shown in figure 4.32.

The combination of the influent, recirculation and return flows yield a wastestream with a flowrate of 10.3 MGD and 42,300 kg/d of PO_4-P which is equivalent to 1.1 mg/L of PO_4-P. More importantly, the microbes of the return sludge which had been releasing PO_4-P in the clarifier sludge blanket are now subjected to an aerobic environment created by the recirculation flow from compartment C to A in the nitrification basin. This aerobic environment in compartment A will now generate an uptake PO_4-P. In Sampling Events 1 and 2, this appears to be evident as the PO_4-P

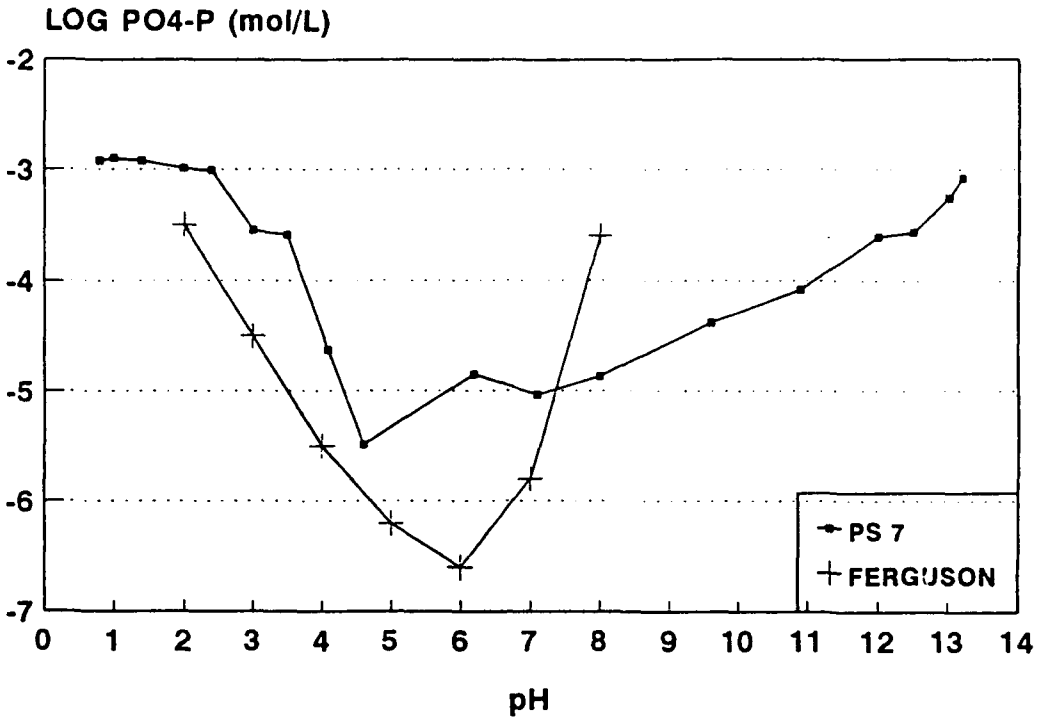
FIGURE 4.32 - MASS LOADING OF PO4-P FOR SAMPLING EVENT 2



levels of the combination of influent, recirculation and return flows entering compartment A are higher than the samples analyzed after the wastestream has nearly completed its course around the outer orbal.

To accurately conclude that the release of PO_4-P was due to anaerobic activity in the sludge blanket of the secondary clarifier, the release of chemically bound PO_4-P into solution must be discounted. The results of Pilot Studies 5 and 7 which analyzed the release of phosphorus into solution under varying pHs indicate that PO_4-P levels are less than 1 mg/L between the pH of 4 and 10. The equilibrium solubility diagram (Ferguson *et al.*, 1973) shown as figure 2.3 is transposed on figure 4.33 in order to compare the results to Pilot Study 7. The solubility curves are similar up to a pH of approximately 7.5, at which point the Pilot Study 7 to rise only gradually. The effects of calcium added to the wastestream in

FIGURE 4.33 - COMPARISON OF SOLUBILITY DIAGRAMS - LOG (PO4-P) VS pH



PS 7 = RESULTS FROM PILOT STUDY 7
FERGUSON = SOLUBILITY DIAGRAM (FERGUSON et al.,1973)

the form of line may account for this difference, but is unmeasurable. During Sampling Event 2, pH of the return sludge averaged 7.1, well within the range of low solubility; thus discounting any substantial release of PO_4-P from chemical compounds.

The assumption that microbes play a significant role in phosphorus removal is strengthened by the analysis of plant alum addition coupled with phosphorus levels recorded during Sampling Events 1-3. Approximately 6.0 mg/L of total phosphorus is removed on a daily basis from the plant with simultaneous precipitation

(chemical and biological). Since less than 3.0 mg/L of total phosphorus is removed chemically by forming metal phosphate complexes (as calculated in Chapter 2.2), more than 3 mg/L of total phosphorus is removed biologically. It can be concluded, however, that ultimately, all phosphorus is removed in solids processing from the secondary clarifier underflow since plant effluent limits do not exceed 0.5 mg/L.

However, the biological phosphorus removed is not of the magnitude of celebrated enhanced biological phosphorus removal plants. Comparison of the orbal system (nitrification basin) to accepted wastewater treatment concepts indicates that this facility has suitable detention times and capacity to support enhanced biological phosphorus removal (BPR). Temperature and pH levels monitored in Sampling Events 1-3 are also suitable for BPR. However, from the pilot studies, it can be concluded that the wastestream and current microbial population are incapable of enhanced BPR without chemical addition. Despite subjecting plant mixed liquor to ideal anaerobic conditions, including the addition of ample substrate, phosphorus release was minimal. Specifically, the phosphorus release using acetate as substrate was significantly less than published experiments. Similarly, luxury uptake of phosphorus was also not observed under ideal aerobic conditions. As a result, attempts to adjust the operation of the nitrification basin to achieve phosphorus removal by strictly biological methods would not be possible.

In summary, the SRP hypothesis conclusions are as follows:

(1) Analysis of present plant conditions indicate that approximately one-half of the plant phosphorus removal is accomplished biologically through incorporation of phosphorus in microbial cells during growth.

(2) The plant design is suitable for BPR, but the wastestream characteristics and/or microbial population will not support enhanced BPR without use of chemical precipitation of metal-phosphate complexes.

(3) The basic anaerobic-aerobic sequence required for biological phosphorus removal appears to be occurring with the secondary clarifier sludge blanket and subsequent return to compartment A of the nitrification basin.

CHAPTER 5
REFERENCES

5.0 REFERENCES

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CHAPTER 6
APPENDICES

APPENDIX A

The flowrate for compressed gasses was determined through linear regression by measuring water displacement from flasks of varying sizes. From the data gathered in figure 6.1, the following quotation was developed:

$$y = 47x - 3.1 \text{ where } x = \text{flowrate (L/min)}$$

$$y = \text{rotometer reading}$$

Table 6.1 - Gas Flowrate Determination

ROTOMETER READING	VOLUME OF FLASK (ml)	TIME (sec)	TIME (min)	FLOWRATE (L/min)
10	250	52	0.87	0.29
30	250	21	0.35	0.71
50	500	27	0.45	1.1
70	500	20	0.33	1.5
90	1000	29	0.48	2.0

APPENDIX B

Table 6.2 - PO_4-P for Sampling Event 1

DAY TIME	PO_4-P (mg/L)				
	INFLUENT	A	B	C	RETURN
1/29 1930	0.96	1.01	0.85	0.76	5.53
2130	0.44	0.73	0.41	0.19	3.17
2330	0.51	1.64	0.70	0.55	4.03
1/30 0130	1.23	2.52	1.14	0.74	5.86
0330	0.53	2.36	0.83	0.38	6.64
0530	0.51	2.45	1.61	1.53	4.74
0730	-	-	-	-	-
0930	0.39	1.82	1.51	0.89	3.30
1130	0.76	1.67	0.57	0.38	5.66
1330	0.50	1.51	0.86	0.59	6.14
1530	0.57	1.59	1.68	1.09	6.80
1730	0.40	1.55	1.55	1.19	7.23
1930	0.42	1.65	2.00	1.13	7.99
2130	0.57	2.25	1.56	1.20	15.8
2330	0.47	3.14	6.29	1.12	8.11
1/31 0130	0.46	3.45	3.22	1.27	8.44
0330	0.50	3.40	2.02	1.20	10.5
0530	0.44	3.47	2.18	1.04	6.95
0730	0.32	5.33	5.91	2.19	4.89
0930	0.40	3.20	5.15	2.50	5.91
1130	0.28	3.14	4.11	1.67	6.34
1330	0.55	2.49	2.38	1.31	7.35
1530	0.39	1.88	1.68	0.79	7.08
1730	0.32	3.83	2.56	1.12	7.00
1930	0.46	2.41	1.87	0.73	3.88
AVG	0.52	2.44	2.19	1.07	6.64

Table 6.3 - Ammonia for Sampling Event 1

DAY TIME	NH_4^+ (mg/L)				
	INFLUENT	A	B	C	RETURN
1/29 1930	13.4	2.18	0.68	0	0.57
2130	14.7	2.00	0.38	0	0.46
2330	15.0	4.83	1.10	0.05	0.59
1/30 0130	14.7	-	-	0.40	0.75
0330	12.2	8.43	7.47	6.50	6.09
0530	8.20	5.29	4.49	3.55	3.53
0730	-	-	-	-	-
0930	5.35	2.63	3.31	4.04	5.21
1130	9.60	4.53	1.77	0	0.66
1330	16.5	4.65	2.03	0.04	0.66
1530	-	-	-	-	-
1730	-	-	-	-	-
1930	15.7	4.42	2.27	0.04	0.31
2130	15.8	10.7	3.73	0.27	0.65
2330	13.4	7.25	3.69	1.17	0.81
1/31 0130	14.4	7.35	2.82	0.77	1.37
0330	18.7	11.8	6.43	0	1.37
0530	15.4	10.6	4.44	0.10	0.47
0730	18.0	8.88	3.63	0.31	0.59
0930	17.7	5.02	2.75	0.24	0.56
1130	16.7	7.59	3.01	0	0.54
1330	21.3	7.86	4.77	0	0.14
1530	26.1	8.93	4.39	0	0.74
1730	20.8	6.26	2.49	0	0.48
1930	25.8	4.02	2.30	0	0
AVG	15.9	6.44	3.24	0.79	1.21

Table 6.4 - Nitrite for Sampling Event 1

DAY TIME	NO_2^- (mg/L)				
	INFLUENT	A	B	C	RETURN
1/29 1930	0	0.14	0.56	0.07	0.01
2130	0	0.32	0.50	0.03	0
2330	0.07	0	0.49	0.11	0.20
1/30 0130	0	0	0.04	0.48	0.28
0330	0.08	0	0.09	0.77	0.13
0530	0	0	0.18	0.50	0
0730	-	-	-	-	-
0930	0.11	0.04	0.01	0	0
1130	0.24	0.05	0.21	0	0.02
1330	0.26	0	0.25	0.15	0.07
1530	0.15	0.06	0.34	0.34	0.05
1730	0.24	0.07	0.40	0.54	0
1930	0.14	0	0	0.59	0
2130	0	0	0.37	0.25	0
2330	0.15	0	0	0.10	0
1/31 0130	0.41	0	0	0.23	0
0330	0.05	0	0.24	0.31	0
0530	0	0	0.22	0.09	0.17
0730	0	0.11	0.11	0.06	0.10
0930	0.04	0.08	0.04	0.05	0
1130	0.44	0.06	0.15	0.08	0
1330	0.33	0.07	0.14	0.29	0.22
1530	0.15	0.07	0.30	0.52	0.25
1730	0.87	0	0.20	0.26	0.05
1930	0.66	0.14	0.31	0.17	0.16
AVG	0.18	0.05	0.21	0.75	0.07

Table 6.5 - Nitrate for Sampling Event 1

DAY TIME	NO_3^- (mg/L)				
	INFLUENT	A	B	C	RETURN
1/29 1930	0	0.01	0.24	1.91	0
2130	0	0.18	0.80	1.86	0
2330	0.15	0	0.66	1.59	0.09
1/30 0130	0	0	0.06	0.97	0.14
0330	0.14	0	0	1.17	0
0530	0.05	0	0.03	0.99	0
0730	-	-	-	-	-
0930	0.43	0	0.07	0.37	0
1130	0	0	0.16	0.63	0
1330	0.01	0	0.12	1.22	0.02
1530	0.24	0	0.21	1.61	0
1730	0	0.02	0.29	1.69	0
1930	0.02	0	0	1.62	0
2130	0.08	0	0.14	1.65	0
2330	0.15	0	0	1.93	0
1/31 0130	0.25	0	0	1.84	0
0330	0.04	0	0.04	2.10	0
0530	0	0	0.04	2.43	0.11
0730	0.34	0.03	0	0.81	0.03
0930	0.44	0.06	0	0.53	0
1130	0.21	0.01	0.02	0.60	0
1330	0.43	0.03	0	1.40	0.26
1530	0.10	0.01	0.21	1.84	0.23
1730	0.33	0	0.12	1.70	0.02
1930	0.28	0.08	0.16	2.18	0.38
AVG	0.15	0.02	0.14	1.44	0.05

Table 6.6 - Mass Loading for Sampling Event 1

DAY TIME	FLOWRATE (MGD) IN	EFF	BASIN 3 FLOW (MGD)	COD (mg/L)	MASSLOAD (BASIN FLOW xCOD) (kg/day)
1/29 1930	7.65	6.60	3.8	400	5800
2130	9.30	7.25	4.7	330	5900
2330	11.1	9.00	5.6	450	9500
1/30 0130	10.8	9.75	5.4	440	9000
0330	6.90	6.10	3.5	360	4800
0530	4.35	4.00	2.2	310	2600
0730	4.50	2.75	2.3	-	-
0930	6.54	5.10	3.3	375	4700
1130	9.75	8.31	4.9	350	6500
1330	7.15	5.71	3.6	400	5500
1530	12.1	10.7	6.1	410	9500
1730	9.69	8.25	4.8	450	8200
1930	7.75	6.50	3.9	440	6500
2130	8.05	6.50	4.1	420	6500
2330	9.45	7.50	4.7	440	7800
1/31 0130	9.60	8.50	4.8	440	8000
0330	7.80	5.70	3.9	340	5000
0530	3.90	3.50	2.0	310	2300
0730	4.75	3.00	2.4	270	2500
0930	5.64	4.00	2.8	250	2700
1130	9.78	7.60	4.9	440	8200
1330	11.4	9.00	5.7	490	10600
1530	9.00	7.80	4.5	330	5600
1730	8.10	7.00	4.1	480	7400
1930	7.20	6.25	3.6	460	6300
AVERAGE	8.09	6.66	4.1	391	6300

Table 6.7 - PO_4-P for Sampling Event 2

DAY TIME	TOTAL P IN (mg/L)	PO_4-P (mg/L)				
		IN	A	B	C	RETURN
2/19 1930	4.5	0	0.38	0	0	6.04
2130	5.7	0	0.11	0	0	6.38
2330	5.1	0	0.64	0	0	7.04
2/20 0130	4.8	0.65	1.63	0.14	0	7.83
0330	5.0	0	1.28	0	0	7.68
0530	5.6	0	0.59	0.05	0	6.77
0730	4.0	0	0.67	0	0	5.59
0930	9.1	0.51	0.37	0	0	4.84
1130	5.0	0	0.45	0	0	2.50
1330	4.7	0.50	0.56	0	0	2.55
1530	4.6	0.43	0.68	0	0	3.03
1730	4.8	0.75	0.54	0	0	3.34
1930	4.9	0.36	0	0	0	6.26
2130	5.2	0.41	0.17	0	0	1.84
2330	5.2	0.76	1.28	0	0	7.82
2/21 0130	4.9	0.97	1.87	0	0	6.95
0330	4.7	0	0.69	0	0	7.22
0530	2.3	0	0.59	0	0	5.63
0730	4.2	0	0.15	0	0	1.57
0930	3.7	0	0.13	0	0	0.96
1130	-	-	-	-	-	-
1330	5.1	0	0.93	0.57	0	3.18
1530	4.0	0.49	0.26	0.97	0	1.79
1730	3.6	0	0.13	1.70	0.04	2.42
1930	4.1	0	0	0.02	0.38	2.71
AVG	4.8	0.24	0.59	0.14	0.02	4.66

Table 6.8 - Ammonia for Sampling Event 2

DAY TIME	NH_4^+ (mg/L)				
	IN	A	B	C	RETURN
2/19 1930	-	-	-	-	-
2130	-	-	-	-	-
2330	15.2	4.17	1.73	0.17	2.45
2/20 0130	13.7	5.33	2.61	1.13	2.30
0330	13.1	4.58	1.58	0	2.53
0530	10.9	3.03	0.53	0	1.67
0730	10.1	2.22	0.20	0	1.04
0930	17.4	2.46	0.16	0.16	0.79
1130	18.4	8.15	6.06	5.52	13.8
1330	19.3	11.5	5.66	4.33	7.16
1530	22.5	12.4	8.82	5.06	15.2
1730	19.4	14.9	9.36	6.65	14.3
1930	18.6	10.5	7.42	4.08	13.9
2130	18.1	9.62	6.27	3.98	12.9
2330	17.3	13.7	6.64	5.07	26.3
2/21 0130	16.0	13.8	7.86	6.29	14.4
0330	14.0	9.06	3.55	4.51	16.7
0530	-	-	-	-	-
0730	-	-	-	-	-
0930	-	-	-	-	-
1130	-	-	-	-	-
1330	-	-	-	-	-
1530	-	-	-	-	-
1730	-	-	-	-	-
1930	-	-	-	-	-
AVG	16.7	8.36	4.56	3.13	9.70

Table 6.9 - Nitrite for Sampling Event 2

DAY TIME	NO_2^- (mg/L)				
	IN	A	B	C	RETURN
2/19 1930	0.46	0	0.85	0.20	0
2130	0.34	0	0.98	0.21	0
2330	0.42	0	0.43	0.54	0
2/20 0130	0	0	0.26	0.73	0
0330	0	0	0.82	1.04	0
0530	0	0	0.49	0.06	0
0730	0.12	0	0.19	0	0
0930	0.09	0	0.20	0	0
1130	0	0	0.63	0.07	0
1330	0.45	0	0.48	0.98	0
1530	0.01	0	0.90	1.46	0
1730	0.48	0	1.16	1.85	0
1930	0.27	0	1.78	2.44	0
2130	0.40	0	1.75	1.16	0
2330	0	0	0.90	1.36	0
2/21 0130	0	0	1.21	1.72	0
0330	0	0	1.74	2.05	0
0530	0.04	0.01	0.66	0.06	0
0730	0	0.23	0	0	0.05
0930	0	0.07	0	0	0.01
1130	-	-	-	-	-
1330	0	0.01	0.63	0.17	0.10
1530	0.38	0.02	1.08	0.97	0.31
1730	0.26	0.07	1.08	1.00	0.03
1930	0.28	0.01	0.85	0.14	0
AVG	0.17	0.01	0.79	0.76	0.02

Table 6.10 - Nitrate for Sampling Event 2

DAY TIME	NO_3^- (mg/L)				
	IN	A	B	C	RETURN
2/19 1930	0.66	0	1.35	2.18	0
2130	1.01	0	1.33	2.48	0
2330	0.56	0	0.39	1.47	0
2/20 0130	0	0	0	0.43	0
0330	1.57	0	0.62	1.48	0
0530	2.03	0	0.68	1.42	0
0730	1.14	0	0.41	0.77	0
0930	0.29	0	0.58	0.89	0
1130	0	0	0.69	1.26	0
1330	0	0	0.47	1.34	0
1530	0	0	0.98	1.59	0
1730	0	0	1.22	2.09	0
1930	0	0	1.84	3.03	0
2130	0	0	2.17	3.55	0
2330	0	0	1.01	2.39	0
2/21 0130	0	0	1.08	1.75	0
0330	0	0	1.74	2.77	0
0530	0.19	0	2.25	3.19	0
0730	0.60	0	2.08	2.53	0
0930	0.18	0	0.97	1.55	0
1130	-	-	-	-	-
1330	0	0.19	1.09	2.18	0.02
1530	0	0	1.48	3.24	0
1730	0.38	0	1.45	3.38	0
1930	0.37	0	1.78	2.10	0
AVG	0.37	0.01	1.15	2.04	0.00

Table 6.11 - Mass Loading for Sampling Event 2

DAY TIME	FLOWRATE INFLUENT (MGD)	BASIN 1 FLOW (MGD)	COD (mg/L)	MASSLOAD (BASIN 1 Flow x COD) (kg/day)
2/19 1930	7.2	3.6	450	6100
2130	7.4	3.7	400	5600
2330	7.6	3.8	450	6500
2/20 0130	8.0	4.0	400	6100
0330	5.8	2.9	350	3800
0530	4.85	2.4	275	2500
0730	5.25	2.6	300	3000
0930	6.2	3.1	400	4700
1130	6.3	3.2	300	3600
1330	7.4	3.7	375	5300
1530	8.15	4.1	400	6200
1730	7.7	3.9	425	6300
1930	8.2	4.1	500	7800
2130	7.8	3.9	500	7400
2330	8.9	4.5	475	8100
2/21 0130	8.75	4.4	450	7500
0330	6.6	3.3	400	5000
0530	5.25	2.6	300	3000
0730	5.1	2.6	175	1700
0930	5.9	3.0	250	2800
1130	7.7	3.9	-	-
1330	7.20	3.6	350	4800
1530	7.7	3.9	400	5900
1730	7.4	3.7	375	5300
1930	7.35	3.7	425	6000
AVG	7.0	3.5	380	5200

Table 6.12 - Temperature and pH for Sampling Event 2

DAY TIME	pH		TEMP (°C)	
	INFLUENT	RETURN	INFLUENT	RETURN
2/19 1930	9.7	7.2	15.8	16.4
2130	9.9	7.2	16.3	16.3
2330	9.2	7	-	-
2/20 0130	8.3	7	-	-
0330	10.1	7	-	-
0530	10.7	7	-	-
0730	9.1	7.1	-	-
0930	10.1	7.2	15.8	15.4
1130	9.3	7.2	16.4	16.2
1330	9.0	7.2	16.9	16.7
1530	9.0	7.2	16.8	16.6
1730	8.7	7.1	16.5	16.4
1930	9.0	7.3	16.5	16.4
2130	9.0	7.3	15.4	16
2330	8.7	6.9	-	-
2/21 0130	8.7	6.8	-	-
0330	10.0	6.8	-	-
0530	10.5	6.9	-	-
0730	9.5	7.1	-	-
0930	10.4	7.2	-	-
1130	-	-	-	-
1330	9.9	7.2	17.6	16.9
1530	9.0	7.2	17.1	16.8
1730	9.7	6.9	16.9	16.7
1930	9.6	7.3	15.5	15.9
AVG	9.5	7.1	16.4	16.4

Table 6.13 - Other Phosphorus Levels for Sampling Event 2

SAMPLE DESCRIPTION	DATE - TIME	TOTAL P (mg/L)
Influent Plant - Composite	2/20	6.0
Influent Event Average	2/20	5.2
Effluent Plant - Composite	2/20	0.21
Effluent - Grab	2/20 - 1030	0.92
Effluent - Grab	2/20 - 1200	0.15
Clarifier Effluent - Grab	2/26 - 1900	1.9
Effluent Plant - Composite	2/26	0.87

Table 6.14 - Total Phosphorus by Plant Lab Analysis for Sampling Event 3

LOCATION	ANALYZER	TYPE	TOTAL P (mg/L)
Influent	Lab tech	24 hr composite	8.1
Effluent	Lab tech	24 hr composite	0.31
Effluent	Plant operator	Grab (a.m.)	0.26
Effluent	Plant operator	Grab (p.m.)	0.24
After Cl contact chamber	Plant operator	Grab (a.m.) east west	0.29 0.13
After Cl contact chamber	Plant operator	Grab (p.m.) east west	0.31 0.13

Table 6.15 - PO_4-P at the Secondary Clarifier (2^o) and Plant Flowrates for Sampling Event 3

TIME	FLOW (MGD)			PO_4-P (mg/L)		
	EAST IN	WEST IN	TOTAL EFF	IN 2^o	EFF 2^o	RECYCLE 2^o
3/6 0830	5.3	1.2	3.5	0.43	0.23	1.1
1000	5.8	1.5	5.2	0.51	0.21	1.1
1130	7.6	2.0	7.6	0.37	0.21	1.3
1300	9.0	2.4	8.1	0.50	0.24	1.7
1430	9.1	2.3	9.3	0.52	0.24	1.5
1600	8.8	2.2	7.7	0.50	0.25	1.5
AVG	7.6	1.9	6.9	0.47	0.23	1.4

Table 6.16 - PO_4-P, DO and pH in Reactors A and B for Pilot Study 1

TIME (min)	A			B		
	pH	DO (mg/L)	PO_4-P (mg/L)	pH	DO (mg/L)	PO_4-P (mg/L)
0	7.0	5.6	0.37	7.1	5.6	0.35
20	7.8	9.3	0.43	7.8	0	0.46
40	7.9	8.4	0.76	8.1	0	0.86
60	7.9	9.1	0.96	8.2	0	0.92
80	8.0	9.0	0.75	8.2	0	1.04
100	7.9	9.0	0.84	8.3	0	1.05
120	7.9	9.1	0.82	8.3	0	1.30
140	8.0	8.8	0.96	8.3	0	1.30
160	7.9	8.8	0.86	8.3	0	1.45
180	7.9	8.7	0.84	8.4	0	1.73
200	8.0	8.8	0.82	8.4	0	1.63
220	7.9	8.9	0.84	8.4	0	1.73
240	7.9	8.9	0.89	8.4	0	1.74
260	8.0	8.9	0.86	8.4	0	1.73

Table 6.17 - PO_4-P, DO and pH in Reactors A-C for Pilot Study 2 (PO_4 and DO results in mg/L)

TIME	A			B			C		
MIN	pH	DO	PO_4-P	pH	DO	PO_4-P	pH	DO	PO_4-P
0	7.6	3.2	0.16	7.6	3.2	0.19	7.1	2.9	0.17
20	8.0	0.8	0.26	8.1	0	0.31	7.8	0	0.70
40	8.2	9.7	0.29	8.2	0	0.37	8.1	0	1.00
60	8.2	8.8	0.32	8.4	0	0.42	8.2	0	1.22
90	8.3	8.7	0.35	8.5	0	0.50	8.3	0	1.37
120	8.3	8.6	0.38	8.5	0	0.55	8.3	0	1.46
150	8.3	8.6	0.40	8.5	0	0.61	8.3	0	1.50
180	8.3	8.6	0.40	8.5	0	0.68	8.3	0	1.54
210	8.3	8.5	0.43	8.6	0	0.99	8.3	0	1.58
240	8.3	8.5	0.45	8.6	0	1.09	8.3	0	1.62
270	8.3	8.5	0.45	8.6	0	1.23	8.4	0	1.62
300	8.3	8.5	-	8.7	0	1.53	8.3	0	1.59
360	8.3	8.5	0.61	8.6	0	1.80	8.3	0	1.69
420	8.3	8.7	0.66	8.6	0	1.86	8.3	0	1.66
480	8.3	8.8	0.61	8.7	0	1.82	8.2	0	1.67

Table 6.18 - Soluble COD (S_s) for Pilot Study 2

REACTOR SAMPLE	S_s (mg/L)
Influent at t=0	56
"A" at t=480 min	32
"B" at t=480 min	104
"C" at t=480 min	200

Table 6.19 - PO_4-P, DO and pH in Reactors A-C for Pilot Study 3 (PO_4-P and DO results in mg/L)

TIME	A			B			C		
min	pH	DO	PO_4-P	pH	DO	PO_4-P	pH	DO	PO_4-P
0	7.5	0.6	0.2	7.4	0.8	0.2	6.2	0.3	0.2
20	7.9	8.4	0.24	7.7	0.1	0.27	7.5	0.1	0.68
40	8.0	8.3	0.27	7.9	0	0.33	7.7	0	1.15
60	8.0	8.2	0.28	8.1	0	0.44	7.8	0	1.47
90	8.1	8.1	0.31	8.1	0	0.88	8.0	0	1.61
120	8.1	8	0.32	8.1	0	1.23	8.0	0	1.58
150	8.1	8	0.32	8.1	0	1.8	8.1	0	1.54
180	8.1	7.9	0.33	8.1	0	2.1	8.1	0	1.52
210	8.1	7.8	0.33	8.2	0	2.12	8.2	0	1.48
240	8.1	7.7	0.34	8.2	0	2.08	8.2	0	1.44
260	8.0	7.8	0.36	8.0	3.3	1.43	8.1	2.9	1.29
280	8.0	7.7	0.37	7.9	5.1	0.89	8.1	3.7	1.21
300	8.0	7.6	0.4	7.9	6.2	0.64	8.2	4.6	1.15
330	8.0	7.5	0.39	7.9	6.9	0.45	8.3	5.0	1.11
360	8.0	7.4	0.4	7.9	6.8	0.33	8.1	7.3	0.77
390	8.0	7.4	0.39	8.0	7.2	0.27	8.1	7.7	0.61

Reactor A: aerobic from t=0 to t=390
Reactors B and C: anaerobic from t=0 to t=240 and aerobic from t=240 to t=390

Table 6.20 - Soluble COD (S_s) for Pilot Study 3

REACTOR SAMPLE	S_s (mg/L)
Influent at t=0	21
"A" at t=390	22
"B" at t=390	21
"C" at t=390	27

Table 6.21 - PO_4-P, S_s and pH in Reactors A-C for Pilot Study 4 (PO_4-P and S_s results in mg/L)

TIME	A			B			C		
(min)	pH	S_s	PO_4-P	pH	S_s	PO_4-P	pH	S_s	PO_4-P
0	7.6	33	0.36	7.5	252	0.31	7.4	786	0.31
30	8.3	10	0.59	8.2	237	0.83	6.7	722	0.26
60	8.4	27	0.73	8.4	175	1.16	7.4	631	0.37
90	8.4	31	0.85	8.4	230	1.24	7.7	724	0.50
120	8.5	29	1.05	8.5	233	1.29	7.8	734	0.64
150	8.6	27	1.54	8.5	238	1.29	7.7	659	0.69
180	8.6	47	1.92	8.5	238	1.29	7.8	600	0.69
210	8.6	40	2.04	8.5	241	1.29	7.8	736	0.71
240	8.6	40	2.12	8.5	237	1.30	7.8	679	0.77

Table 6.22 - PO_4-P in Reactors A and B for Pilot Study 5

SAMPLE	A		B	
	pH	PO_4-P (mg/L)	pH	PO_4-P (mg/L)
1	7.2	0.29	7.1	0.28
2	6.8	0.29	7.5	0.33
3	6.4	0.37	7.9	0.40
4	6.0	0.44	8.4	0.52
5	5.5	0.51	8.9	0.66
6	5.0	0.41	9.4	0.77
7	4.5	0.20	9.9	0.64
8	4.0	0.57	10.5	0.67
9	3.6	3.9	11.0	0.78
10	3.1	15	11.5	1.1
11	2.6	31	12.0	1.7
12	2.1	-	12.5	3.0
13	1.8	-	12.8	10

Table 6.23 - PO_4-P and S_s in Reactors A and B for Pilot Study 6 (PO_4-P and S_s results in mg/L)

	A			B		
TIME	pH	S_s	PO_4-P	pH	S_s	PO_4-P
0	7.5	55	0.28	6.8	103	0.38
30	7.9	-	0.40	8.0	-	1.03
60	8.2	44	0.66	8.2	95	1.44
90	8.3	-	1.12	8.2	-	1.59
120	8.3	40	1.54	8.3	94	1.56
150	8.3	-	1.62	8.4	-	1.64
180	8.3	43	1.65	8.4	103	1.62
210	8.3	-	1.71	8.4	-	1.65
240	8.4	43	1.73	8.4	108	1.68

Table 6.24 - PO_4-P and S_s in Reactors C and D for Pilot Study 6 (PO_4-P and S_s results in mg/L)

	C			D		
TIME	pH	S_s	PO_4-P	pH	S_s	PO_4-P
0	6.4	188	0.38	6.2	312	0.29
30	7.9	-	0.98	7.7	-	0.94
60	8.1	180	1.27	8.1	293	1.09
90	8.2	-	1.36	8.1	-	1.17
120	8.3	193	1.32	8.3	301	1.13
150	8.3	-	1.31	8.2	-	1.10
180	8.3	234	1.28	8.3	307	1.08
210	8.3	-	1.28	8.3	-	1.08
240	8.3	231	1.27	8.3	329	1.06

Table 6.25 - PO_4-P in Reactors A and B for Pilot Study 7

SAMPLE	A		B	
	pH	PO_4-P (mg/L)	pH	PO_4-P (mg/L)
1	7.1	0.28	7.1	0.28
2	6.2	0.44	8.0	0.42
3	4.6	0.1	9.6	1.3
4	4.1	0.72	10.9	2.6
5	3.5	8.0	12.0	7.6
6	3.0	8.8	12.5	8.4
7	2.4	30	13.0	17
8	2.0	32	13.2	26
9	1.4	37	-	-
10	1.0	39	-	-
11	0.8	37	-	-

Table 6.26 - PO_4-P, Soluble COD (S_s) and pH in Reactor A for Pilot Study 8

TIME (min)	pH	DO (mg/L)	PO_4-P (mg/L)	S_s (mg/L)
0	7.5	10.4	101	0
30	7.5	8.8	103	-
60	7.2	8.9	101	11
90	7.2	8.9	100	-
120	7.2	8.9	99.5	3
150	7.3	8.9	101	-
180	7.2	8.7	92.5	14
210	7.2	8.7	101	-
240	7.2	8.8	100	4

Table 6.27 - PO_4-P, Soluble COD (S_s) and pH in Reactor B for Pilot Study 8

TIME (min)	pH	DO (mg/L)	PO_4-P (mg/L)	S_s (mg/L)
0	6.2	0.2	81.5	526
30	7.3	4.9	68.3	421
60	7.2	5.0	65.3	300
90	7.2	5.3	64.4	214
120	7.2	6.9	61.8	171
150	7.3	6.8	59.2	163
180	7.2	6.9	58.3	142
210	7.3	6.7	56.4	136
240	7.2	6.8	56.0	127

Table 6.28 - PO_4-P Recovery for Pilot Study 9

TOTAL PO_4-P ADDED (mg/L)	PO_4-P MEASURED (mg/L)	RECOVERY (%) (PO_4-P ADDED ÷ PO_4-P MEASURED)
15	14.2	95
20	19.2	96
25	24.2	97
30	28.2	94
35	32.6	92
40	36.6	91
45	40.9	91
50	44.9	90

Table 6.29 - PO_4-P, Soluble COD (S_s) and pH in Reactor A for Pilot Study 9 (0 mg/L COD added)

TIME (min)	pH	DO (mg/L)	PO_4-P (mg/L)	S_s (mg/L)
-1	6.8	0.2	44.9	14
0	6.8	0.2	45.6	8
30	6.8	7.7	44.0	14
60	6.7	7.2	44.2	13
90	6.6	7.5	43.9	15
120	6.6	7.6	43.1	14
150	6.5	7.6	42.7	16
180	6.5	7.5	43.1	12
210	6.4	7.8	42.4	22
240	6.4	7.7	42.1	13

Table 6.30 - PO_4-P, Soluble COD (S_s) and pH in Reactor B for Pilot Study 9 (400 mg/L COD added)

TIME (min)	pH	DO (mg/L)	PO_4-P (mg/L)	S_s (mg/L)
-1	6.8	0.2	45.0	21
	5.5	0.2	43.8	335
30	6.5	8.2	41.6	303
60	6.7	7.3	40.7	275
90	6.9	7.6	39.6	210
120	7.1	7.6	37.4	190
150	7.3	7.2	35.8	118
180	7.5	6.7	32.1	65
210	7.5	8.1	31.4	67
240	7.4	8.2	30.3	65

Table 6.31 - PO_4-P, Soluble COD (S_s) and pH in Reactor A for Pilot Study 10 (0 mg/L COD added)

TIME (min)	pH	DO (mg/L)	PO_4-P (mg/L)	S_s (mg/L)
-1	7.4	4.0	51.5	16
0	7.4	<1.0	51.0	20
30	8.0	8.5	50.2	25
60	8.0	8.4	49.8	17
90	8.0	8.4	49.1	33
120	7.9	8.5	49.2	20
150	7.8	8.3	48.9	21
180	7.8	8.3	49.3	22
210	7.7	9.1	49.0	18
240	7.6	8.3	48.8	17

Table 6.32 - PO_4-P, Soluble COD (S_s) and pH in Reactor B for Pilot Study 10 (120 mg/L COD added)

TIME (min)	pH	DO (mg/L)	PO_4-P (mg/L)	S_s (mg/L)
-1	7.4	4.0	51.0	30
0	6.8	<1.0	51.2	121
30	8.0	8.2	48.8	84
60	8.2	8.1	49.3	39
90	8.2	8.9	48.5	35
120	8.2	8.8	48.6	35
150	8.2	8.7	48.6	35
180	8.2	8.7	48.2	29
210	8.2	8.8	48.1	24
240	8.2	8.5	47.6	20

Table 6.33 - PO_4-P, Soluble COD (S_s) and pH in Reactor C for Pilot Study 10 (240 mg/L COD added)

TIME (min)	pH	DO (mg/L)	PO_4-P (mg/L)	S_s (mg/L)
-1	7.1	4.2	53.3	44
0	7.0	2.5	52.8	247
30	7.7	7.8	52.2	235
60	7.9	7.8	51.5	-
90	8.1	7.8	51.1	153
120	8.2	7.8	50.9	-
150	8.2	8.6	49.7	96
180	8.2	8.8	49.9	-
210	8.1	8.7	49.1	62
240	8.1	8.6	49.3	44

Table 6.34 - PO_4-P, Soluble COD (S_s) and pH in Reactor D for Pilot Study 10 (480 mg/L COD added)

TIME (min)	pH	DO (mg/L)	PO_4-P (mg/L)	S_s (mg/L)
-1	7.1	4.2	53.1	27
0	6.4	3.0	53.2	427
30	7.2	8.4	51.9	391
60	7.5	8.4	51.4	-
90	7.7	8.4	50.8	286
120	7.9	8.2	49.6	-
150	8.1	8.1	49.4	195
180	8.2	8.5	48.6	-
210	8.3	8.4	47.8	113
240	8.2	8.9	47.4	91

Table 6.35 - PO_4-P, Soluble COD (S_s) and pH in Reactor A for Pilot Study 11
Raw Waste (1.5 L) + Mixed liquor (0.5 L)

TIME (min)	pH	DO (mg/L)	PO_4-P (mg/L)	S_s (mg/L)
0	9.1	5.0	6.72	110
30	8.9	8.0	6.89	103
60	8.7	8.1	7.04	-
90	8.5	8.1	7.15	-
120	8.4	8.2	7.18	74
150	8.3	8.3	7.24	-
180	8.2	8.3	7.24	-
210	8.3	8.3	7.19	63
240	8.2	8.3	7.14	63

Table 6.36 - PO_4-P, Soluble COD (S_s) and pH in Reactor B for Pilot Study 11
Tap Water (1.5 L) + Mixed liquor (0.5 L)

TIME (min)	pH	DO (mg/L)	PO_4-P (mg/L)	S_s (mg/L)
0	7.3	8.1	12.6	12
30	7.4	8.0	12.6	9
60	7.3	8.2	12.7	-
90	7.3	8.3	12.9	-
120	7.3	8.4	13.0	16
150	7.3	8.5	12.4	-
180	7.2	8.6	12.7	-
210	7.2	8.6	13.0	13
240	7.1	8.6	12.6	13

Table 6.37 - PO_4-P, Soluble COD (S_s) and pH in Reactor A for Pilot Study 12 (0 mg/L COD added)

TIME (min)	pH	DO (mg/L)	PO_4-P (mg/L)	S_s (mg/L)
0	7.0	<1.0	45.9	27
30	7.0	6.5	45.1	43
60	6.9	6.4	44.7	36
120	6.7	7.5	44.1	19
180	6.7	8.2	43.3	27
240	6.6	7.9	43.1	17

Table 6.38 - PO_4-P, Soluble COD (S_s) and pH in Reactor B for Pilot Study 12 (400 mg/L COD added w/HCO_3)

TIME (min)	pH	DO (mg/L)	PO_4-P (mg/L)	S_s (mg/L)
0	7.0	<1.0	45.4	391
30	7.6	7.6	45.1	313
60	7.9	7.7	44.8	300
120	8.2	7.6	44.0	146
180	8.3	7.4	42.7	100
240	8.2	7.9	42.7	88

Table 6.39 - PO_4-P, Soluble COD (S_s) and pH in Reactor B for Pilot Study 12 (400 mg/L COD added w/o HCO_3)

TIME (min)	pH	DO (mg/L)	PO_4-P (mg/L)	S_s (mg/L)
0	7.1	<1.0	46.7	371
30	7.6	7.8	45.9	315
60	7.8	7.8	45.5	260
120	8.1	7.7	44.8	156
180	8.3	7.6	44.2	99
240	8.2	8.0	43.5	80

Table 6.40 - PO_4-P, Soluble COD (S_s) and pH in Reactor A for Pilot Study 13 (0 mg/L COD added)

TIME (min)	pH	DO (mg/L)	PO_4-P (mg/L)	S_s (mg/L)
0	7.0	3.4	46.3	28
30	7.1	8.3	45.7	19
60	7.1	8.1	46.1	19
120	6.8	8.0	45.6	17
180	6.7	8.1	-	19
240	6.6	8.2	43.1	16

Table 6.41 - PO_4-P, Soluble COD (S_s) and pH in Reactor B for Pilot Study 13 (400 mg/L COD added w/HCO_3)

TIME (min)	pH	DO (mg/L)	PO_4-P (mg/L)	S_s (mg/L)
0	7.0	2.0	46.5	386
30	7.7	7.9	46.0	186
60	7.8	7.7	46.1	166
120	8.1	7.9	45.4	100
180	8.3	8.0	44.1	90
240	8.2	8.3	43.3	71

Table 6.42 - PO_4-P, Soluble COD (S_s) and pH in Reactor B for Pilot Study 13 (400 mg/L COD added w/o HCO_3)

TIME (min)	pH	DO (mg/L)	PO_4-P (mg/L)	S_s (mg/L)
0	7.0	2.0	46.2	399
30	7.6	7.9	46.1	246
60	7.8	7.8	45.8	214
120	8.1	7.8	45.4	179
180	8.3	7.9	44.5	101
240	8.2	8.5	43.6	89